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ABSTRACT

This training course and a companion course titled "Design of Systems for Solar Heating and Cooling of Residential Buildings," are designed to train home designers and builders in the fundamentals of solar hydronic and air systems for space heating and cooling and domestic hot water heating for residential buildings. Each course, organized in 22 modules, provides 44 hours of instruction. The modularized structure of the training courses provides considerable latitude in organization and presentation, especially with regard to the time period over which the course could be presented. Included in each course are directed periods for computational practice, inspection of working systems, and "hands-on" experience with models. Course standards and needs were developed by interacting with architects, engineers, builders, contractors, and installers of heating, ventilating, and air conditioning systems in residential buildings. From the standards and needs, objectives for the course were developed and the curricular materials prepared. (Author/MLF)

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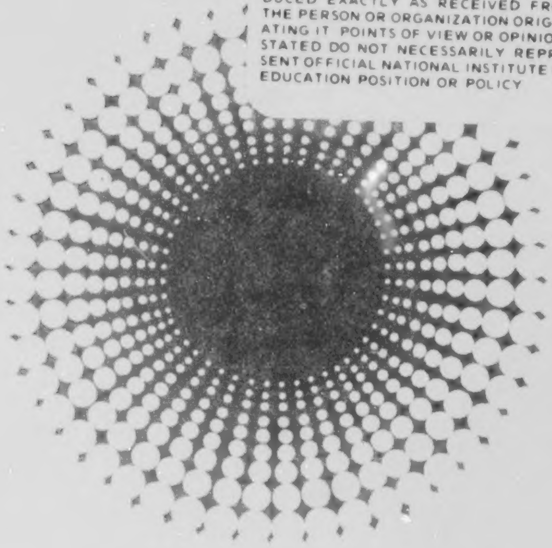

SOLAR HEATING AND COOLING OF RESIDENTIAL BUILDINGS
SIZING, INSTALLATION AND OPERATION OF SYSTEMS

Prepared by
SOLAR ENERGY APPLICATIONS LABORATORY
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SOLAR ENERGY APPLICATIONS LABORATORY
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PREFACE

The primary purpose of this training course is to develop the capability of practitioners in the Home Building industry to Size, Install and Operate Solar Heating and Cooling Systems for Residential Buildings. The goal is to have this course implemented nationwide to train practitioners in the requisite skills to integrate solar energy systems into residential buildings.

Recent estimates indicate that a substantial amount of domestic space and water heating in the United States will be accomplished by solar energy in the near future. However, significant implementation can only be achieved if substantial capabilities are created among the professions and trades in the building industry to install solar systems.

This training course, and a companion course titled Design of Systems for Solar Heating and Cooling of Residential Buildings, are courses to train home designers and builders in the fundamentals of solar hydronic and air systems for space heating and cooling and domestic hot water heating for residential buildings. The modularized structure of the training courses provides considerable latitude in organization and presentation, especially with regard to the time period over which the course could be presented. At Colorado State University, the course is presented in five continuous days, but a longer period of time utilizing evening hours could be used just as effectively. The structure also provides for verification that participants have achieved anticipated levels of understanding. At CSU, validation is in the form of daily evaluations by the participants especially with regard to material content and methods of presentation. The instructors interact and respond to the evaluations and alter their methods of presentation to meet the needs of particular groups of trainees.

COURSE DEVELOPMENT

This training course was developed by the staff of the Solar Energy Applications Laboratory and vocational education specialists at Colorado State University in cooperation with the NAHB Research Foundation, Inc., Rockville, Maryland. A national advisory committee was established to provide advice and general guidance to the project staff regarding direction and content of the training courses. The committee members are from various sectors of the home-building industry, and also teachers, architects, engineers and representatives from governmental agencies.

In determining curriculum content, a rigorous procedure was followed to develop course standards and needs by interacting with architects, engineers, builders, contractors and installers of heating, ventilating and air conditioning systems in residential buildings. From the standards and needs, objectives for the course were developed and the curricular materials were then prepared.

ABOUT THE AUTHORS

This manual for the training course was prepared with the cooperative efforts of many people under the organizational efforts of Dan S. Ward. The program for development of both the Design and the Installation courses was directed by Susumu Karaki with George O. G. Löf as senior advisor. The authors of this manual have, individually and collectively, considerable experience in the design, installation, operation and maintenance of solar systems for space heating and cooling and domestic hot water heating. A short biographical sketch of the authors and their contributions to the manual are hereafter described.

Dan S. Ward -- Dr. Ward joined the staff of the Solar Energy Applications Laboratory at Colorado State University in 1973 and presently serves as Assistant Director of the Laboratory as well as Assistant Professor of Civil Engineering and Physics. Since 1973 he has conducted research in solar heating and cooling systems, and has taught courses in solar energy applications.

Dan Ward has considerable experience with solar heating and cooling systems including supervision of design, construction and installation of the solar systems in three Solar Houses at Colorado State University. He is chairman of the ASTM subcommittee on development of standards for testing solar energy systems, and has published many papers and written several reports on heating and cooling systems.

Prior to joining the CSU faculty, he was a home building contractor in Houston, Texas,and this experience in addition to his knowledge of solar systems has proved to be very valuable, especially with regard to this training course.

Besides organizing and directing the development of this training course, Dr. Ward also had principal responsibility for the preparation of the following modules of the manual: Module 3, Introduction to Solar Heating and Cooling Systems; Module 12, Operations Laboratory; Module 19, Scheduling of Solar Installations; Module 22, Future Prospects for Solar Heating and Cooling Systems.

Susumu Karaki -- Dr. Karaki has been a member of the faculty at Colorado State University for the past 19 years. He is Associate Director of the Solar Energy Applications Laboratory and Professor of Civil Engineering. Being involved in solar energy research since 1973, he has directed a number of research projects in solar energy utilization. Susumu Karaki has served on several committees of the International Solar Energy Society, and has been a member of U.S. teams for international information exchange on solar energy utilization.

In addition to directing the activity for development of the two training courses, Dr. Karaki was principally responsible for: Module 2, Course Orientation; Module 9, Solar Cooling Systems; Module 15, System Economics; Module 16, Solar Sizing Calculations.

George O.G. Löf -- Dr. Löf has specialized in solar energy utilization for over thirty years and pioneered in the development of solar heating and cooling systems. As Director of the Solar Energy Applications Laboratory, he is responsible for the considerable progress made in development of solar systems at Colorado State University and elsewhere. His accomplishments have earned him worldwide recognition and among his many awards is the Lyndon Baines Johnson award for outstanding service to mankind.

George Löf served as chairman of the advisory committee that guided the development of these practical courses and was senior advisor to the staff. Additionally, he prepared the following modules: Module 7, Service Hot Water Systems; Module 21, Buyer's Guide.

Charles C. Smith -- Mr. Smith's background experience includes design and installation of a variety of solar heating and cooling systems for various sized buildings. He was involved in the design, installation, and operation of the liquid heating solar system in CSU Solar House I, air-heating solar system for a school building, a small scale residential-greenhouse combination structure, and a heating system for a fish hatchery. The variety of solar systems with which he has been associated includes those for agricultural uses and food processing applications.

Charles Smith was principally responsible for the preparation of the following modules in this manual: Module 6, Thermal Storage Subsystems; Module 8, Solar Space Heating Systems; Module 10, Solar Heating and Cooling Systems; Module 18, Retrofit Considerations. Additionally, he participated significantly in preparing Module 7, Service Hot Water Systems; Module 11, Control Subsystems.

Michael Z. Lowenstein -- Dr. Lowenstein is Professor of Chemistry at Adams State College in Alamosa, Colorado and has specialized in energy education. He serves as consultant to the Energy Research and Development Administration in the public information program on energy in the State of Colorado. During his sabbatical leave from Adams State College, he served for one year at Colorado State University and participated in the preparation of this training manual. Mike Lowenstein's principal contributions are: Module 1, Energy Problem; Module 4, Solar Radiation; Module 17, Cost Effectiveness of Energy Conservation; Module 20, Constraints and Incentives.

C. Byron Winn -- Dr. Winn is Professor of Mechanical Engineering and has been actively involved in solar heating and cooling systems since 1973. He has designed and installed both liquid and air-heating solar systems in seven residences, and thereby has gained considerable practical experience.

Byron Winn organized and directed the development of a training course for Design of Systems for Solar Heating and Cooling of Residential Buildings, which is a companion course to this one. His principal contributions to this manual are: Module 11, Control Subsystems and Module 12, Operations Laboratory.

Milton E. Larson -- For the past 25 years, Dr. Larson has been engaged in educational work, with technical education and trade and industrial education as the focus of activity. He is Professor of Vocational Education at Colorado

State University and has served as head teacher-trainer for technical education in the Department of Vocational Education for the last eleven years.

Milton Larson, along with Dr. Valentine, provided expert advice to the staff in developing the training course and this manual.

Ivan E. Valentine -- Dr. Valentine, along with Dr. Larson, served the staff who prepared this manual as a vocational education specialist. He has considerable experience in curriculum development in all areas of technical education and has, additionally, practical experience as a consulting engineer, and also as a heating and plumbing contractor.

Ivan Valentine's extensive experience in vocational technical education contributed significantly to the development of this practical training course and manual.

NAHB RESEARCH FOUNDATION, INC.

The NAHB Research Foundation through Ralph J. Johnson, Staff Vice President and Director, and H.W. Anderson contributed considerably to the development of the training course and this manual. Mr. Johnson, in particular, carries with him over 30 years experience in housing and home-building research. The NAHB Research Foundation has been involved with the use of solar energy in housing for nearly twenty years and participated in the development of many standards for housing and home building.

The staff participated directly in the preparation of Module 19, Scheduling of Solar Installations, and Module 20, Constraints and Incentives.

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The staff is especially indebted to Wendy Asa and Kathi McKenna for preparing and organizing the manuscripts for this manual. Their patience and service are truly appreciated.

ADDITIONAL ACKNOWLEDGMENTS

The following tables and charts were obtained from the Climatic Atlas of the United States, U.S. Department of Commerce, Environmental Science Services Administration, Environmental Data Service, June 1968:

Table 4-4, Mean Daily Solar Radiation (from page 70)
Figures 4-8 through 4-19, Mean Daily Solar Radiation Maps (from pages 69 and 70)
Table 13-2, Data Values for Heating Load Computations (from page 36).

In addition, Table 13-1, Values of R, U, and 1/k for structural materials, is condensed from larger tables contained in Chapter 21, ASHRAE Handbook of Fundamentals, 1972, ASHRAE, New York.

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SIZING, INSTALLATION, AND OPERATION OF SOLAR HEATING AND COOLING SYSTEMS

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FOR
RESIDENTIAL BUILDINGS

MODULE 1

ENERGY PROBLEM

SOLAR ENERGY APPLICATIONS LABORATORY
COLORADO STATE UNIVERSITY
FORT COLLINS, COLORADO

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GLOSSARY OF TERMS

breeder reactor	A nuclear fission reactor which converts the 99.3 per cent of natural uranium that can't be used for reactor fuel into plutonium, which can be used for reactor fuel.
deuterium	A form of hydrogen in which each atom is twice as heavy as a normal hydrogen atom.
doubling time	The time required for the size of a quantity to double under exponential growth. Give by the equation: Double time = 70 years/% growth.
exponential growth	An increasing growth - the type of growth that occurs when the size of the growth depends on the size of the quantity growing.
far-term future	The period from the year 2000 on.
fossil fuels	Coal, petroleum, natural gas.
geothermal	Literally "Earth heat".
hydroelectric	The use of the energy of falling water to spin a turbine to produce electricity.
linear growth	Straight line growth - the type of growth that occurs when the growth is by a constant amount each year.
near-term future	The next 10 - 30 years, through the year 2000.
nuclear fission	The splitting of an atom of uranium or plutonium to form two lighter atoms and release a large amount of energy in the form of heat.
nuclear fusion	The reaction that occurs in the sun. Two atoms of deuterium are joined together to form a single atom of helium. A large amount of energy is released in the form of heat.
passenger mile	Moving one passenger one mile.
reactor-year	The operation of one reactor for one year.
solar	Referring to the sun.
ton mile	Moving one ton one mile.
wind	The movement of air over the surface of the earth. Caused by heating of the surface by the sun.

INTRODUCTION

There are many people today who realize that there is a serious energy problem in the United States. Much has been written and said about the energy situation, but it is still difficult to understand why, after years of plentiful and cheap energy, there should suddenly seem to be a smaller amount of energy available, and only at higher prices. The issue is confused by various authorities and organizations issuing contradictory reports as to the magnitude of the problem. In this module the current energy situation is examined from a historical view point and with a look into the future.

OBJECTIVE

The objective of the trainee is to understand the energy problem so that utilization of solar energy on a national scale can be kept in proper perspective. At the end of this module the trainee should be able to:

1. Identify the concept of exponential growth,
2. Recognize the problems associated with trying to meet increasing demands with limited resources,
3. Realize the part that conservation can play in meeting future energy needs,
4. Describe the potential and limitations of:
    a. Fossil fuels
    b. Nuclear energy
    c. Geothermal energy
    d. Wind energy

e. Hydroelectric energy

f. Solar energy

THE ENERGY PROBLEM

Energy, like commodities, is expected to follow the laws of supply and demand. If demand exceeds supply there will be a shortage. In most situations a shortage will result in a price increase; the prospects of higher profits will prompt more production; the supply will increase to meet the demand. The energy situation, however, differs from the normal situation in several ways. Regulations on the price of energy often require that it be sold at a cost below the real market value. Rather than encouraging increased supplies, such price regulations tend to reduce the interest of producers to increase the supply. And even when a supply increase is desirable, there are natural and unnatural limits beyond which the supply cannot be increased, no matter what the price. Finally, the demand for energy seems to be increasing rapidly and without limit. The combination of these factors, operating outside the laws of supply and demand, is what makes the energy problem so serious.

GROWTH OF DEMAND

There are two basic ways in which a quantity can grow; linearly or exponentially. These growth modes are illustrated in Figure 1-1 using as an example two misers who are saving money.

The solid line represents a miser who saved ten dollars a year by stuffing it under the mattress of his bed. Every ten years he stashes away $100, so that when twenty years have passed, he has $200; thirty years, $300; etc. The money stashed away is an example of "linear growth"

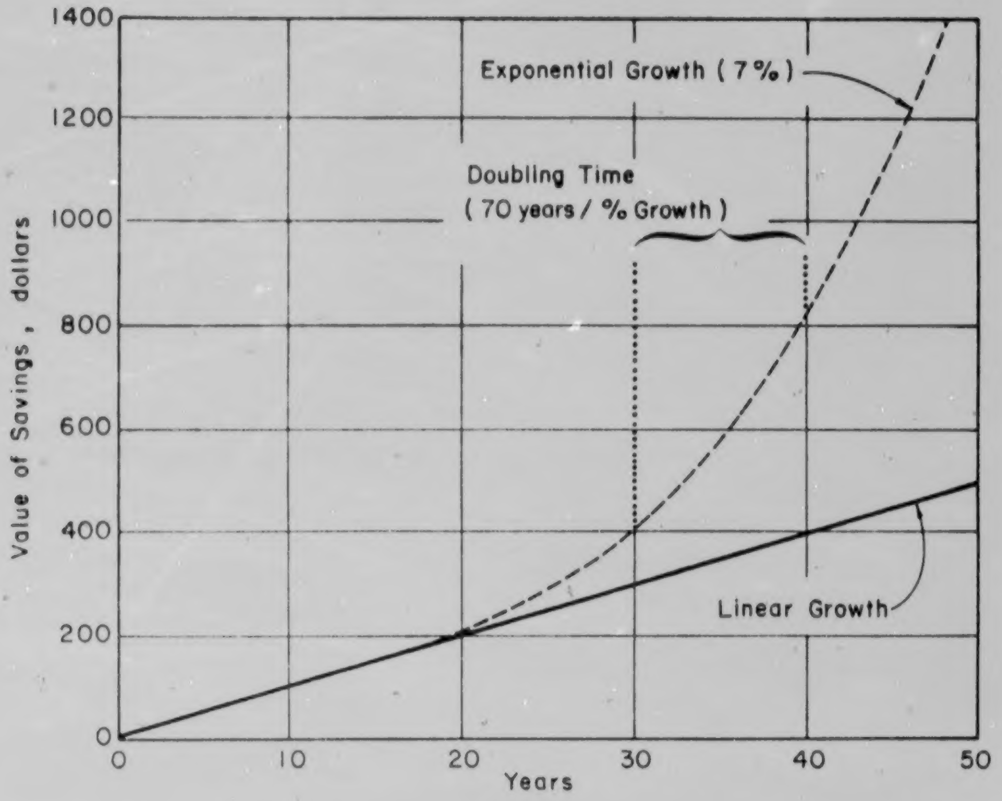

Figure 1-1. Growth Modes - Linear and Exponential

in which the growth is by a constant amount each year. The dashed line represents a miser who decides after ten years to take his $100 out of the bed and to invest it in a savings account at seven per cent interest. At the end of twenty years the account is worth $200; in thirty years, $400; in forty years, $800; without any deposit beyond the original $100. Money invested at interest is an example of "exponential growth" in which the size of the growth depends on the size of the quantity that is growing. Shown in the figure is the "doubling time", the time required for the size of the growing item to double. Note that the doubling time depends on the growth rate.

Many natural processes exhibit exponential growth. The energy situation is directly influenced by the world population, which is growing exponentially as shown in Figure 1-2.

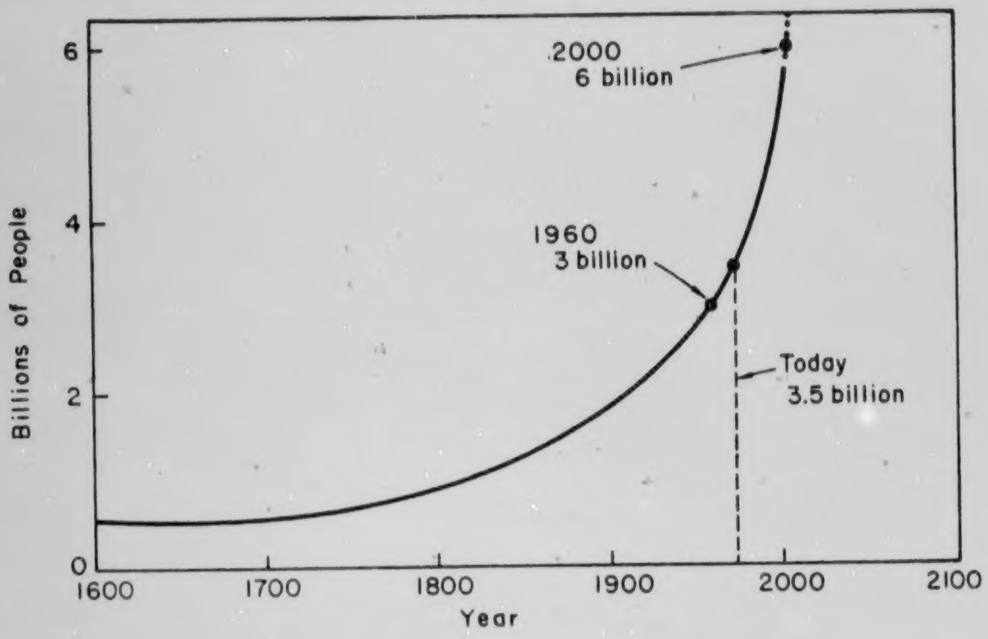

Figure 1-2. Growth of World Population

According to current trends, the population of the world will reach six billion by the year 2000 - almost twice the current population. (At the present growth rate of two and one-half per cent, the doubling time for population is 28 years.) If energy demand increased along with population, twice as much energy would be needed by 2000. In fact, energy demand is growing faster than population and the need to triple the world energy supply is anticipated.

Figure 1-3 (a through d) illustrates some other exponential processes that affect the energy situation.

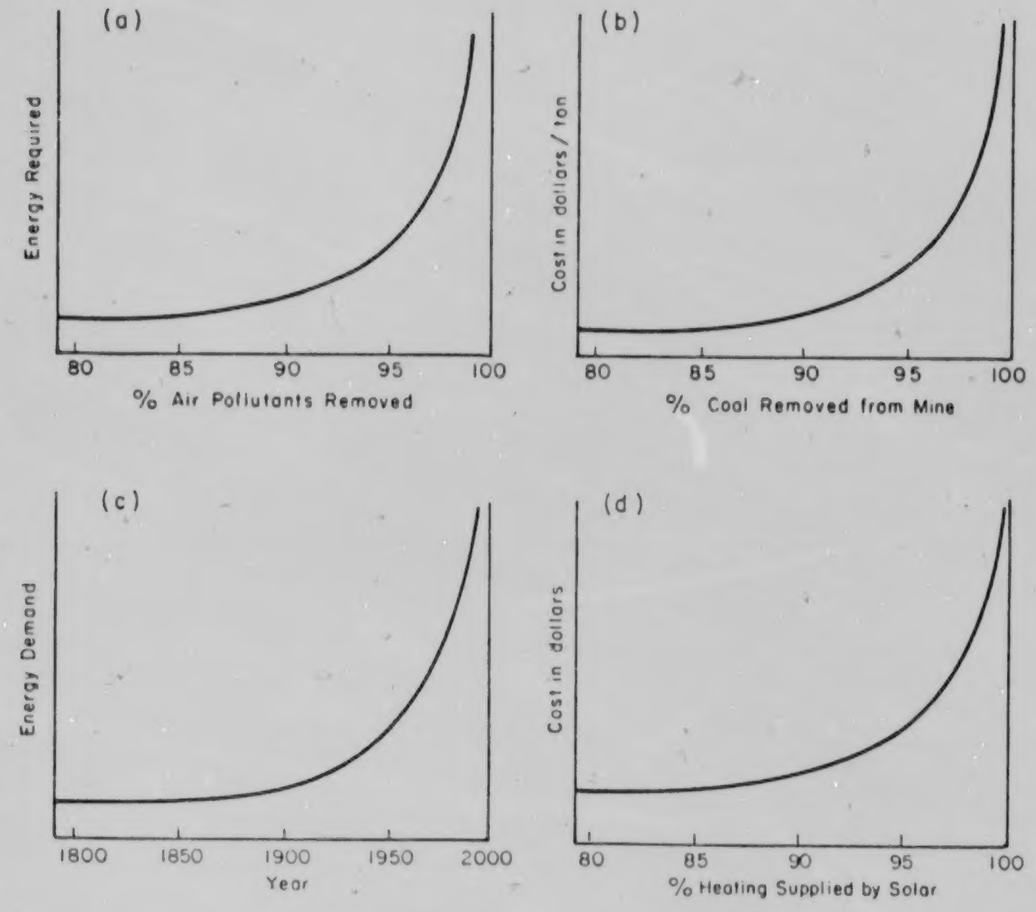

Figure 1-3. Exponential Processes Related to Energy

UNITED STATES ENERGY PROBLEM

The worldwide energy situation has particular impact on the United States, since we have always been large users of energy. (Our high standard of living can be linked directly to high energy use.) The economic boom of the 1960's resulted in a high level of surplus income, most of which was spent on energy -consuming luxuries. Second cars, motor homes, snowmobiles, speedboats - all became a way of life for United States citizens. All used large amounts of energy, both in the manufacturing process and for operation. The demand for leisure time resulted in major changes in industry and agriculture with a decrease in tedious labor at the expense of increase in the use of energy.

The advent of the "environmental movement", also in the 1960's, had a very significant effect on the energy situation. The actual implementation of pollution controls on industry required the expenditure of large amounts of energy (Figure 1-3-a). At the same time that energy demands were increasing, restrictions were placed on the supply of energy. Nuclear power plants were delayed; coal power plants were restricted; off-shore drilling for oil was halted; the Alaskan pipeline was delayed; and supply started to fall short of demand. The oil embargo widened the gap between supply and demand and since that time we have become increasingly aware of the fact that not only is energy going to become more scarce, it is going to cost more - probably a good deal more.

THE ENERGY FUTURE

Two periods can be identified in the future. The first is the "near future", a period of twenty to thirty years up to the year 2000. The second is the "far future", starting at 2000 and continuing on for an undetermined time. The solutions to the energy problem are different for these two periods and each period must be examined separately.

The Near Future

The near future must be characterized both by an increase in energy supply and a decrease in demand.

Demand Decrease - Since the largest factor causing increased demand is the growing population, a world-wide plan for population control will be required. Unless the exponential growth of population can be halted, energy supply will continue to lag behind demand. Demand can also be decreased by conservation measures. Recycling has the potential to save energy as does the redesign of consumer goods to emphasize long life and repairability. Appliances and automobiles can be designed to use energy more efficiently. (The conservation of energy in homebuilding is discussed in Module 17). Some alterations of life style can produce energy savings. As an example, a shift in federal policy from building airports to support of railroads would result in a large increase in the efficiency of freight transportation (Table 1-1). There is, however, a limit to the amount of energy that can be saved by conservation measures without major changes in life style that may not be acceptable, and conservation alone cannot eliminate the gap between energy supply and demand. Conservation can extend the period before the energy situation becomes critical, thus providing more time for the development of new technology.

Table 1-1. Energy Efficiency of Transportation

ENERGY EFFICIENCY FOR PASSENGER TRANSPORT

ITEM	BTU PER PASSENGER MILE URBAN	BTU PER PASSENGER MILE INTERCITY
BICYCLE	200	
WALKING	300	
BUSES	3700	1600
RAILROADS		2900
AUTOMOBILES	8100	3400
AIRPLANES		8400

ENERGY EFFICIENCY FOR FREIGHT TRANSPORT

ITEM	BTU PER TON MILE
PIPELINE	450
RAILROAD	670
WATERWAY	680
TRUCK	3,800
AIRPLANE	42,000

Supply Increases - In the near future the major portion of our energy supply must come from known and developed technologies. It has traditionally taken twenty to thirty years from the development of a new technology to its commercial application and there is no evidence that this time period can be significantly shortened. For the next twenty-five years the energy supply must come from fossil fuels, hydroelectric dams, and nuclear reactors. It is useful to examine the potentials of each of these energy supplies.

Fossil Fuels - The fossil fuels consist of coal, oil, and natural gas. These are found in the earth at depths ranging from less than a hundred feet to several miles. Fossil fuels have been formed from animal and vegetable matter deposited between ten and a hundred million years ago. While the processes that formed these fuels are still going on today, as far as mankind is concerned, once the present supplies are used up, there will be no more fossil fuels. In addition to the problem of limited supply, the use of fossil fuels is complicated by environmental problems, both in the extraction and burning of the fuel.

Coal - Large, low sulfur coal fields in the United States are found in the Western states - Wyoming, Montana, and Colorado. Many of these fields are found near the surface and are suitable for strip mining. The strip mining of these coal deposits is meeting opposition from many citizens of the states involved. The primary concern of the citizens is the environmental impact of strip mining. There has been some success in Eastern states with the restoration of stripped land to beneficial use. However, in the water-short West, restoration is still in the experimental stage. Until this matter is resolved, resistance to strip mining will continue.

For deep mining to provide large amounts of coal in the future, new methods of mining must be developed that are not dependent on a large labor force. (There seem to be few people who are willing to become coal miners.) A large increase in the number of mining engineers will be required. There is also the problem of coal supply. While the United States has large amounts of coal, the supply is not infinite (Figure 1-4), and the cost of extracting coal goes up rapidly as the supply is exhausted (Figure 1-3-b). When all the facts are considered, the production of large amounts of coal is not a simple task.

Petroleum - Any consideration of oil as an energy source raises the question of the impact on the economy of large payments for foreign oil and the environmental dangers posed by large scale off-shore drilling. There is also a great deal of controversy over the amount of oil that is available on earth. While the major oil companies claim that supplies are dwindling, others say that the lack of reserves has come about because the oil companies are not looking very hard for oil. However, whether oil will run out in fifty or two hundred years, there is no question that oil cannot be regarded as a long-term future energy supply (Figure 1-5).

Natural Gas - While there is also controversy over the available amount of natural gas, there is general agreement that it is the most limited of the fossil fuels. United States reserves have been decreasing steadily for the last ten years and natural gas shortages have already been experienced in some areas of the country. The more optimistic estimates suggest that natural gas will be essentially gone within thirty years; pessimists say ten years. Natural gas is certainly not a long-term future energy source (Figure 1-6).

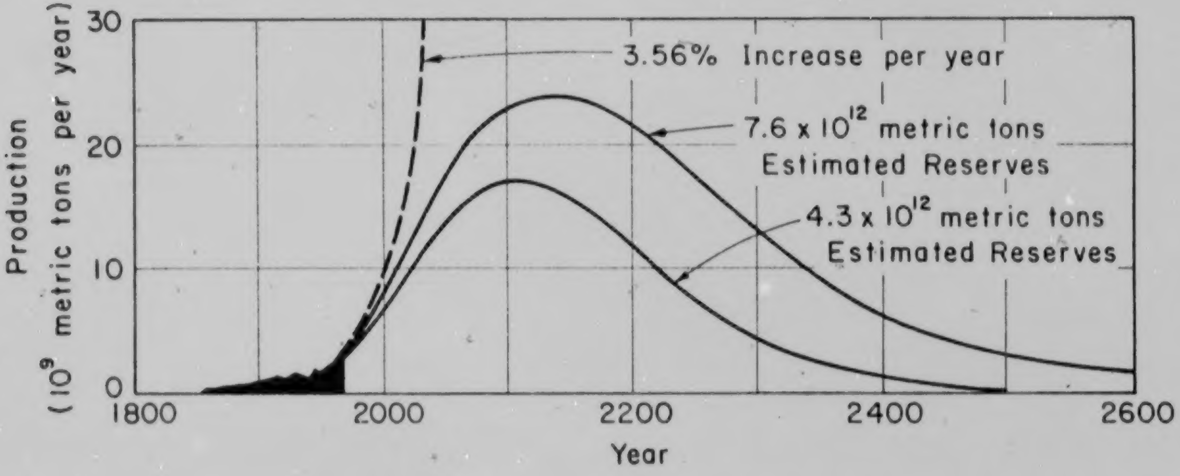

Figure 1.4. Cycle of World Coal Production

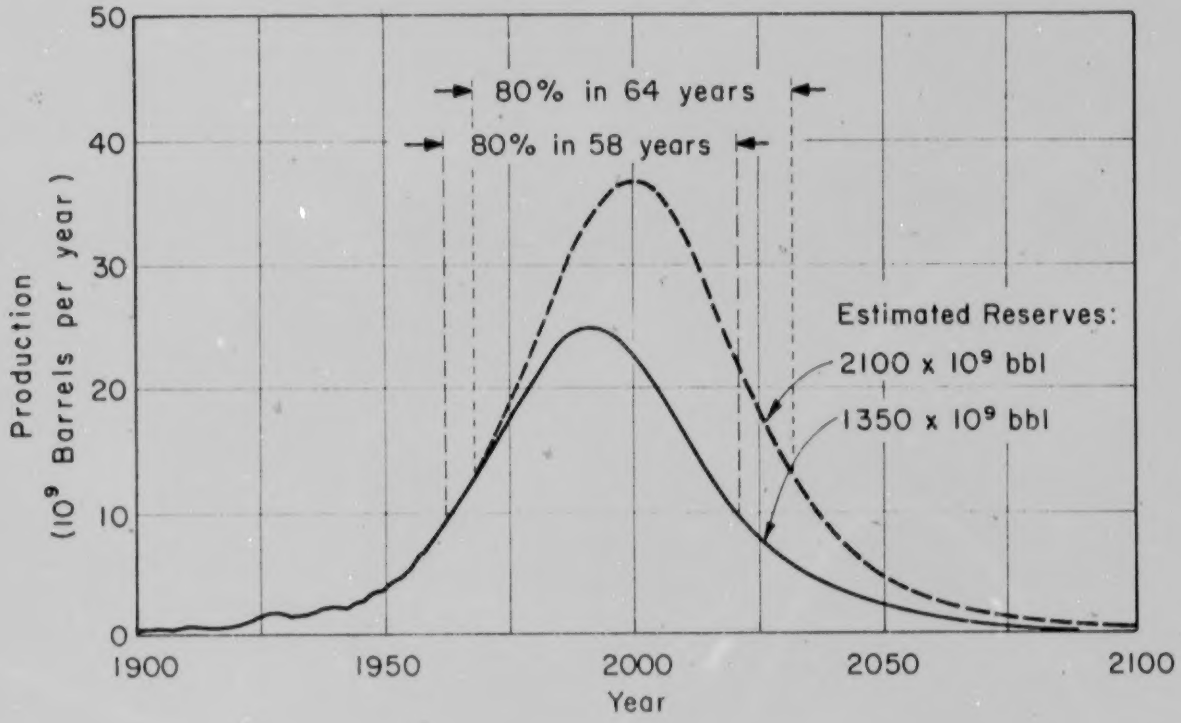

Figure 1-5. Cycle of World Oil Production

The dashed curve reflects Ryman's estimate of $2,100 \times 10^6$ barrels and the solid curve represents an estimate of $1,350 \times 10^9$ barrels.

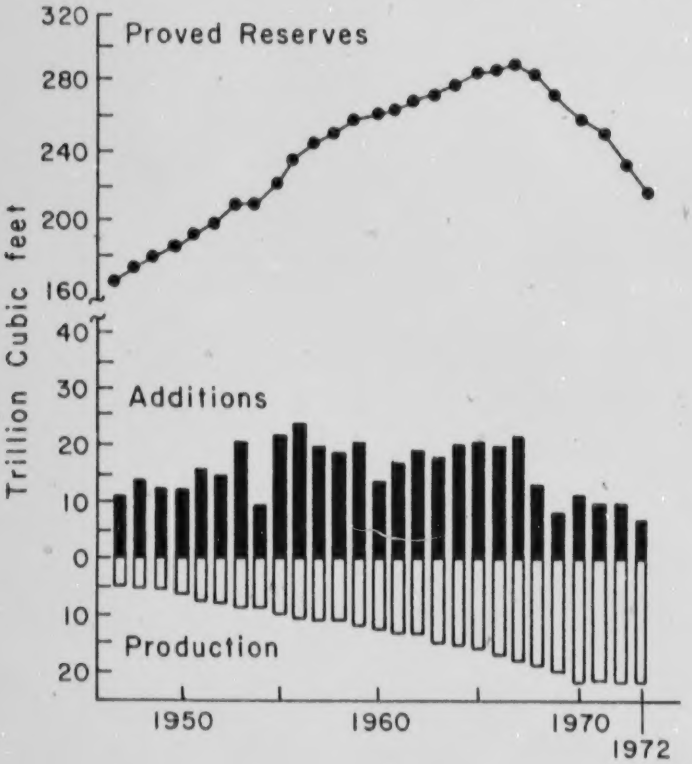

Figure 1-6. U.S. Natural Gas Reserves (Excluding Alaska)

Nuclear Fission - The potential for the supply of electrical energy from nuclear fission has already been well demonstrated. At present about nine percent of our national electrical energy demands is satisfied by nuclear energy. It is anticipated that, by 1985, nuclear reactors will be producing almost twenty percent of our electrical energy and, by 2000, fifty percent. This anticipated growth of nuclear generation raises some serious doubts and fears in the minds of the public which must be answered if the industry is indeed to grow as expected.

Fuel Supply - Present reactors can use only about 0.7 percent of natural uranium as fuel. Current uranium reserves can be expected to supply present and future reactors past the year 2000. By the time these reserves are depleted, the breeder reactor, which converts the remaining

99.3 percent of the unusable uranium into a useful fuel, plutonium, should be on line. The breeder reactor promises a nuclear fuel far into the future, perhaps as much as a thousand years.

Safety - The nuclear power industry has a remarkable safety record. To date there has not been a single injury or death attributable to radiation in a commercial power plant. The industry has accumulated 175 reactor-years of operation and the U.S. Navy has 1300 reactor-years of operation, all without a single accident.

Despite this impressive safety record, there is a segment of the public that is demanding a halt in the construction of new reactors and a shutdown of those already operating because they are "unsafe". A horrible scenario is envisioned by the critics of nuclear power in which a reactor explodes, nuclear material is scattered through the air, and millions die. In fact, there have been some serious accidents at nuclear power plants and in every case the multiple-redundant safety systems shut down the reactor with no human injury and no leakage of radioactive materials. An exhaustive study of nuclear technology was completed in 1975, known as the "Rasmussen Report" after the scientist in charge of the study. The conclusion of the study is that the probability of being killed by a nuclear reactor accident is lower than the probability of being struck by a meteorite -- about one chance in 300,000,000. In contrast, the probability of being killed in an automobile accident is about one chance in 4,000.

Waste Disposal - Nuclear power plants produce small quantities of highly radioactive waste that will require long-term storage. A technique has been developed to convert this waste into a solid glass-like material that can be easily stored. At present, the site for long-term storage has not been selected, but by the time appreciable amounts of wastes accumulate, twelve to fifteen years from now, it is expected that a satisfactory storage site will be available.

Hydroelectric - Hydroelectric power has traditionally been thought of as a "clean" form of energy in that it causes no emissions. However, it is not without environmental effect. The creation of a large lake out of what was previously a free-flowing river causes environmental changes resulting in the death of some species and the growth of others. There is also evidence that the creation of large lakes can cause climatic variations over wide areas. The "wild rivers" legislation has been passed to protect some rivers and the public is increasingly opposed to large hydroelectric projects. Even if we ignore these considerations, the potential contribution of hydroelectric power in the United States is small. If every possible river were dammed, less than four percent of our estimated electrical needs in the year 2000 would be met.

Summary, Near Future - In the next ten to thirty years our energy will have to come from known technology. The fossil fuels (primarily coal), nuclear, and hydroelectric are currently available. All of these technologies are in use today and are safe and reliable. We cannot afford to ignore or prohibit any one of the three without serious consequence to production of goods and services. Conservation of energy will serve to reduce the anticipated shortages of energy and provide a little more time for the development of long-term energy technology.

Far Future

Energy for long-term use will come from technologies which are now being developed or perfected. The breeder reactor has been previously mentioned as a means of extending nuclear fission into the future. Several other technologies will now be mentioned. While this list is not all-inclusive, it illustrates the kinds of energy sources that are being considered.

Wind - Wind energy is one of the oldest forms of energy used by man, having been used since biblical times for moving ships and since the fifteenth century for powering machinery. For certain isolated locations, where conventional electrical energy is unavailable, wind power is already being used. However, the feasibility of generating significant amounts of energy for national needs has not been demonstrated. To generate one megawatt requires a windmill about 180 feet in diameter on a 200 foot tower, with an average wind velocity of 30 miles per hour. Thousands of towers would be needed to replace one coal generating plant. Recently a large-scale demonstration wind generator has been built but the technology is still several years from being perfected. While wind may be utilized in some portions of the country, it is unlikely to be significant in meeting our needs in the near future.

Geothermal - Geothermal power generation utilizes the heat of the earth to produce steam to run turbines. Theoretically, the extent of geothermal energy is unlimited. However, practically, there are limitations to its use. Geothermal steam produces several environmental effects. If dry steam is obtained, a rare occurrence, problems come from noxious gasses that are found with the steam. Hot geothermal water is extremely salty, containing as much as twenty percent dissolved salts (ocean water contains about three and one-half percent). The disposal of this water is a problem, since it is much too salty to be dumped into streams. The water can be reinjected into the earth when cool, but this requires using some of the energy that was generated. In some areas pumping out large quantities of water has caused the land to sink. Finally, useful geothermal energy is found only in a few locations. The geysers steam field near San Francisco, California is the only large developed geothermal site in the United States. Its capacity of 400 megawatts is less than ten percent of the area's energy needs. Because of the many problems encountered, geothermal energy must still be classified as in the "development" stage.

Nuclear Fusion - Nuclear fusion is the reaction that occurs in the sun and involves the joining of two atoms of heavy hydrogen (deuterium) to form an atom of helium. When this occurs, at a temperature of over ten million degrees, a large amount of energy is released. The problem is controlling and containing this reaction to make it occur slowly enough so that useful energy can be obtained. To date, efforts to carry out a controlled nuclear fusion reaction in the laboratory have been unsuccessful. The problems are significant and it is possible that nuclear fusion may never be successfully utilized. If experiments do succeed (some are predicting success within ten years), the generation of useful energy will still be many years in the future.

Solar - Solar energy represents a potentially large energy source. One-half of one percent of the land area in the United States receives enough radiation to supply all the energy we need in the year 2000. Technically it is possible to utilize solar energy to generate electricity, heat homes, and produce steam. The major problem is that solar energy is diffuse and is received on the earth's surface at low intensity. A 100 megawatt solar thermal power plant requires over a million square feet (23 acres) of collectors. The technological design of such a power plant is now being investigated and the next few years should result in determination of the feasibility of large-scale solar electricity generation.

Organized efforts on the use of solar energy for home heating have been going on since the 1940's. However, it is only recently, with the sudden increases in the cost of fossil fuels, that large scale efforts have been made toward developing this technology. In some areas where fuel costs are high, solar heating can compete successfully today. As fuel prices rise and the technology improves, solar heating will play an increasingly larger part in meeting future energy needs.

A reasonable goal by the year 2000 is for one-third of new construction and one-third of old construction to be fitted with solar heating systems. One must be cautiously optimistic about solar heating since, if this goal is met, the energy supplied by solar heating would be only about five percent of the national energy used.

SUMMARY

Table 1-2 is a summary of some future energy choices and their likely impact. It must be observed that our choice seems not to be "which resource should be developed", but rather, "how can we develop all our resources and encourage conservation to avoid serious energy shortages?"

Table 1-3 contains energy saving suggestions by elementary school children. If each of us exerts a maximum effort, we may be able to come up with suggestions at least as good as these.

Table 1-2
Present and Future Energy Sources

Energy Source	Development Status and Prospects for Future Use
FOSSIL FUELS	
Petroleum	Now widely used. Supplies limited - possibly exhausted in 30 - 40 years
Natural gas	Now widely used. Supplies limited - possibly exhausted in 10 - 20 years
Coal	Now widely used. Some difficulty in extracting - possibly exhausted in 300 - 500 years
HYDROELECTRIC	Now in use. Number of sites for future development is limited
SOLAR	Now in limited use. Needs further technological development. Practicality somewhat dependent on geography, weather patterns, etc.
NUCLEAR	
Conventional fission reactors	Now in limited use. Low-cost fuel supply possibly exhausted in 30 - 40 years. Waste disposal problems
Fast breeder reactors	Now in late stages of development. Greatly extends potential fuel supply of fission reactors. Waste disposal problems
Fusion reactors	Feasibility still to be proven. Fuel supply virtually unlimited
GEOTHERMAL	Now in very limited use. Number of suitable sites for future development is limited
WIND	Now in very limited use. Needs further technological development. Number of suitable sites for future development is limited

Table 1-3

Energy Saving Suggestions (Elementary School Children)

1. Find out if oil has another name besides petroleum and look for it under that name
2. Lower people's body temperature to 68°F
3. Dip everything that's made in stuff that glows in the dark
4. Make it a rule that there has to be at least two people in every big bed that uses an electric blanket
5. Put more hot sauce in the food
6. Don't have so many days of school
7. Don't stay in more than one room at a time

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TRAINING COURSE IN
THE PRACTICAL ASPECTS OF
SIZING, INSTALLATION, AND OPERATION OF SOLAR HEATING AND COOLING SYSTEMS
FOR
RESIDENTIAL BUILDINGS

MODULE 2

COURSE ORIENTATION

SOLAR ENERGY APPLICATIONS LABORATORY
COLORADO STATE UNIVERSITY
FORT COLLINS, COLORADO

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INTRODUCTION

The Solar Energy Applications Laboratory at Colorado State University in cooperation with the NAHB Research Foundation, Inc., of Rockville, Maryland, has developed two practical training courses for the design, installation and operation of solar systems to heat and cool residential buildings. One course is entitled DESIGN OF SYSTEMS and the second course is SIZING, INSTALLATION, AND OPERATION OF SYSTEMS.

Over a period of one week, each course provides 44 hours of instruction, including directed periods for computational practice, inspection of working systems, and "hands-on" experience with models. The courses provide the trainees with practical methods for designing solar systems and important principles which will lead to successful installation and long-term operation of solar energy systems.

PURPOSE

The purpose of this module is to explain the objectives and outline the events for the week-long course for Sizing, Installation, and Operation of Systems. The sequence of topics and the chronology of events are discussed, as well as administrative matters pertaining to the conduct of the course.

SCOPE

This course on Sizing, Installation and Operation of solar systems concerns only residential solar systems. Primary emphasis is placed on heating systems because those solar systems are economical in many regions of the country. Solar cooling systems are not extensively discussed, as they are not as yet economically viable although they are technically feasible. Integrated solar heating and cooling systems are included in this manual as they are practical in areas where solar heating systems can be justified and the cooling components are added to the solar heating system.

The systems discussed in this manual are strictly for residential applications, although the basic principles apply to any solar heating and cooling system. When solar systems are designed for office, commercial or industrial buildings, the users are advised that there may be constraints and other considerations that may necessitate changes in system design characteristics and installation procedures from those discussed in this manual.

ORGANIZATION OF THIS COURSE

The course organization, as shown in Figure 2-1, is arranged in a progressive manner. The trainees will first be introduced to various solar heating and cooling systems, via tours of houses equipped with operational systems, and then a general discussion of the types of currently practical solar systems is planned. Basic characteristics of solar radiation are subsequently explained to establish a working basis for the determination of available solar energy which can be utilized by a solar system. The various components of solar heating and cooling systems and solar water heating systems are then described, followed by methods of integration primarily into new buildings, although the same methods apply to existing buildings.

	SUNDAY	MONDAY	TUESDAY	WEDNESDAY	THURSDAY	FRIDAY
0800		MODULE 2 (45 min) Course Orientation MODULE 3 (75 min) Introduction to Solar H&C Systems	OPEN DISCUSSION (30 min) MODULE 6 (90 min) Thermal Storage Subsystems	OPEN DISCUSSION (60 min) MODULE 10 (60 min) Solar Heating and Cooling Systems	OPEN DISCUSSION (30 min) MODULE 13 (90 min) Heating Load Calculations	OPEN DISCUSSION (30 min) MODULE 17 (90 min) Cost Effectiveness of Energy Conservation
1000		COFFEE (30 min)	COFFEE (30 min)	COFFEE (30 min)	COFFEE (30 min)	COFFEE (30 min)
		MODULE 4 (90 min) Solar Radiation	MODULE 7 (90 min) Service Hot Water Systems	MODULE 11 (45 min) Control Subsystems MODULE 12 (45 min) Operations Laboratory	MODULE 14 (60 min) Solar System Sizing MODULE 15 (30 min) System Economics	MODULE 18 (45 min) Retrofit Considerations MODULE 19 (45 min) Scheduling of Solar Installations
1200		LUNCH (60 min)	LUNCH (60 min)	LUNCH (60 min)	LUNCH (60 min)	LUNCH (60 min)
1300 1400	REGISTRATION Solar House Tours	MODULE 4 cont (60 min) Solar Radiation MODULE 5 (60 min) Fluid-Heating Solar Collectors	MODULE 8 (120 min) Solar Heating Systems	MODULE 12 cont (240 min) Operations Laboratory	MODULE 15 cont (30 min) System Economics MODULE 16 (90 min) Solar System Sizing Calculations	MODULE 20 (60 min) Constraints and Incentives MODULE 21 (60 min) Buyer's Guide
1500		COFFEE (30 min)	COFFEE (30 min)		COFFEE (30 min)	COFFEE (30 min)
		MODULE 5 cont (90 min) Fluid-Heating Solar Collectors	MODULE 8 cont (30 min) Solar Heating Systems MODULE 9 (60 min) Solar Space Cooling Systems		MODULE 16 cont (90 min) Solar System Sizing Calculations	Final Discussion and Critique (90 min)
1700		ADJOURN	ADJOURN	ADJOURN	ADJOURN	ADJOURN
1730	RECEPTION AND DINNER MODULE 1 (30 min) Energy Problem					AWARDS DINNER MODULE 22 Future Prospects for Solar H&C Systems

Figure 2-1. Course Schedule

Opportunity to review the instructional sessions is provided each morning, during which time the participants are encouraged to ask questions to clarify problem areas. Wednesday afternoon is a laboratory period to allow trainees to gain some experience with operating systems and to assemble air and liquid heating model solar systems. General check lists are provided to enable systematic checks of completed systems so that problem areas can be identified. Participants will be allowed to inspect the CSU solar houses thoroughly. The following full day, Thursday, is devoted to the technical and economical sizing of solar systems. Heating load calculations are included because the size and economical cost decisions for a solar facility are dependent upon the annual heating load for the building. Other important considerations which should be assessed in regard to retrofit installations, scheduling of work, component sizing and control instrumentation are discussed on Friday.

Daily evaluations of each module are requested of each participant in this course. The evaluations will assist the instructors in assessing material comprehension and conducting the course effectively.

SYNOPSIS OF COURSE CONTENT

TOUR OF SOLAR HOUSES

A pre-course tour of solar houses in the local area will provide the trainees with the opportunity to see different styles of homes and practical types of solar systems. The solar systems are briefly described and performance of the systems are detailed when such information is available. The duration of the tour is 3 hours.

The tour is concluded with an informal reception and banquet in which the instructors and trainees are introduced. A discussion of the energy problem (Module 1) is presented after the banquet.

MODULE 1. ENERGY PROBLEM

The objective in this module is to bring into perspective the problem of meeting the projected energy demand in the United States with known supplies of fossil fuels. The future availability of energy depends upon reduction of per capita use through effective conservation practices as well as increases in production of coal, oil, and conventional energy forms. Effective conservation necessarily entails the development of alternative sources of energy such as solar, geothermal, wind, and nuclear fusion. An effective balance between supply and demand can be maintained if development of alternative sources is actively pursued. The substance of the presentation is included in this manual.

MODULE 2. COURSE ORIENTATION

This module is employed to explain the objectives and purpose of the course and to outline the sequence of events during the course. All the modules in this course are briefly presented. While participants are encouraged to ask questions during the presentation of the modules, for some modules it may be more effective if questions are held until the presentation has been completed. The instructor will indicate his preference in handling questions.

The objectives of the course are to develop capabilities in trainees to:

1. Choose the type of solar heating and/or cooling system suitable for the particular building and location;
2. Select the size of the solar system that will provide an economical fraction of the annual heating requirements;
3. Install solar systems to operate effectively over a range of load conditions;
4. Identify difficulties in operation of systems and maintain the systems so that they will operate as trouble-free as possible;
5. Explain the technical details of operation and economic value of solar systems.

Daily evaluations will be made by the trainees regarding the material, organization, and methods of presentation for each module. The evaluations will assist the instructors to conduct an effective training course.

MODULE 3. INTRODUCTION TO SOLAR HEATING AND COOLING SYSTEMS

The purpose of this module is to describe the basic arrangements of components for solar heating and cooling systems and to explain the operating principles of different systems. The differences between active and passive systems and hydronic and air systems are explained. The function of controls and the interfacing requirements of the different components are described.

Many graphics are used in the text to illustrate differences between flat-plate and concentrating collectors, direct and diffuse radiation, and air-heating and water-heating solar systems. The integration of a hot water heating unit into a space heating and cooling system is described. The strategy, at the present stage in solar energy system development, is to use a mix of solar and conventional energy. The rationale for this strategy is discussed in the module.

MODULE 4. SOLAR RADIATION

Knowledge of the nature of solar radiation, its distribution in time and variability with weather is of fundamental importance in the design of solar heating and cooling systems. An explanation for the decrease in solar radiation through the earth's atmosphere, as well as the seasonal, monthly, daily and hourly variations in the amount of solar radiation available are given in this module. Two systems of measurement units are presented, with factors for converting from one system to another, in order to fully utilize data sources which record solar energy availability. The basic data are given in the form of radiation maps which are used for sizing solar systems in later modules.

MODULE 5. FLUID HEATING SOLAR COLLECTORS

The solar collector is the principal component in a solar system , and this module describes design and operational characteristics of the presently available practical collectors for residential applications. Design considerations which affect the collector performance are dimensions of the collector, number of glass covers, absorber plate construction, and absorber coatings. They are also related to efficiency of solar heat recovery, operating temperature desired, average outdoor temperature and power requirements. The cost-effectiveness of a collector depends upon many factors, particularly durability, and this module explains preventive maintenance procedures.

In liquid-heating collectors, the concern for corrosion of the absorber tubes, pipes and storage tank is certainly greater than for air-heating collectors. Freeze protection by the addition of ethylene glycol, boiling protection within the system by the use of vents, erosion protection by removal of particulates, and removal of free ions by use of ion getters are discussed.

Graphical presentations of collector efficiencies are made to compare the performances of different liquid collectors but comparison of liquid and air-heating collectors must be made on the basis of system performance. Finally, considerations for assembly of collector modules into an array are presented.

MODULE 6. THERMAL STORAGE SUBSYSTEMS

For solar systems to provide a major fraction of the annual heating requirements for a residential building, thermal heat storage units are needed to store excess energy collected during the day to provide the building heating load during the night. This module explains the different methods for sensible and latent heat storage. Latent heat storage, or phase-change methods, are not yet practical for residential applications.

Principles for selection of storage media, sizing the storage on the basis of collector area, scheduling of unit installation, and operating strategy are discussed. Water storage tanks are recommended for liquid-heating solar systems,and requirements for the structural integrity of the tank are enumerated. Pebble-bed heat storage units are recommended for air-heating solar systems,and container descriptions and installation and operation methods are presented.

MODULE 7. SERVICE HOT WATER SYSTEMS

A solar hot water heater can be used in domestic service water systems in many ways. There are two major types of solar water heaters, circulating and non-circulating, with several design variations of each type. Circulating heaters are likely to be the more widely used type in the United States due to freezing considerations. In its simplest form, a solar water heater consists of a flat-plate water-heating collector and an insulated storage tank positioned at a higher level than the collector. These components, connected to the cold water main and the hot water service piping in the dwelling, can provide most of the hot water requirements in a sunny climate.

Detailed descriptions of many types of solar water heaters are given in the module, coupled with schematic drawings for installation. Procedures for sizing the solar collectors are outlined and examples are worked out. Although costs at present are highly variable, estimates for typical size water heaters are presented.

MODULE 8. SOLAR HEATING SYSTEMS

Basic arrangements of liquid- and air-heating solar systems are described in detail for effective space heating with a solar system. The different modes of solar system operation are explained as well as the function of auxiliary heating units in the systems. Both liquid- and air-heating collection systems are described as to materials, components, and construction.

Domestic hot water heating systems can be integrated into both air and liquid collection loops and the interfacing methodology is presented.

Integration of heat pumps into a solar system is explained but there is insufficient evidence as yet to determine whether heat pumps should be used as auxiliary units in the system or be operated as a solar-assisted heating unit for the building.

MODULE 9. SOLAR SPACE COOLING SYSTEMS

There is presently only one type of space cooling unit with performance data for residential buildings and that is an absorption refrigeration machine. Evaporative cooling, and radiative cooling methods have been explored but neither use solar energy, and are limited in application to specific regions of the country.

Of many possible refrigeration systems available, only absorption systems appear to be economically feasible in the near-term and the lithium-bromide-water unit is currently the only commercially available unit. Absorption refrigeration utilizing a lithium-bromide-water cycle employing a cooling tower is explained, as well as the operating principles for lithium-bromide absorption chillers. Heat pumps in both the heating and cooling modes are described, as well as a solar Rankine-cycle engine which operates with solar energy.

An evaporative cooler and a triethylene glycol open-cycle desiccant system which cools air by dehumidification can be integrated into an air-heating solar system. A possible radiative cooling system is also discussed.

MODULE 10. SOLAR HEATING AND COOLING SYSTEMS

A space cooling system in conjunction with a liquid-heating solar heating system is described. The cooling unit is a lithium-bromide-water absorption refrigeration machine and requires additional components such as a cooling tower, chilled water storage tanks, pumps and associate piping, valves, and controls.

For use in arid or semi-arid regions of the country where evaporative cooling may be employed, an evaporator cooling unit added to an air-heating solar system is described. The rock bed storage unit is used for cool storage.

MODULE 11. SOLAR SYSTEM CONTROLS

The purpose of controls in a solar system is to maximize the use of solar energy in the heating and/or cooling system. Solar system controls are automatic so that the occupant of a building need only be concerned with setting a thermostat. The controls consist of relays which switch electric valves and pumps in the liquid system or blowers and dampers in the air system, in respose to temperatures or temperature differences. Recommendations are provided for thermostat types and other temperature sensors and locations.

The control logic for a hydronic system with temperature sensor settings is reviewed as to the sequence of events in both the heating and cooling demand modes. The control logic for an air system with an evaporative cooler and domestic hot water heating system is also indicated. To incorporate auxiliary heat control into a solar system, the pump or blower must be actuated from a control center rather than directly by the thermostat.

MODULE 12. OPERATIONS LABORATORY

The operations laboratory, scheduled for the midpoint in the course, will provide the trainees with some hands-on experience with models and operating solar systems. Useful check lists are provided to identify areas where problems may be occurring. Readings are given in sample check lists and the trainees are to determine if the system is operating as desired. When readings indicate a malfunction within the system, the trainees are to determine the source of the problem and corrective procedures.

MODULE 13. HEATING LOAD CALCULATIONS

Although determining the building heating load is a standard procedure in the HVAC industry, many procedures are simplified and approximate, because to size a furnace more detailed procedures are not justified. However, with solar systems, the approximate procedures can lead to large system costs because heating loads for buildings are generally overestimated. For the purpose of sizing solar systems, more detailed heating load calculations are recommended and the reward will be an economical solar system.

MODULE 14. SOLAR SYSTEM SIZING

Solar systems are sized to provide a major fraction of the total annual heating load. A simple procedure based on average conditions for "typical" air and hydronic systems is presented to calculate collector area. From the collector area determined, the sizes of other components are established. Rules of thumb are given to guide the user in sizing the entire system from a given collector area.

Alternatively, the fraction of annual heating load supplied by the solar system can be calculated for an arbitrarily sized collector area. The worksheets provided in the module organize the calculations.

MODULE 15. SYSTEM ECONOMICS

The economics of solar heating systems depends upon the first cost of systems, conventional energy costs, inflation rates, mortgage payments, property tax, insurance, credits on income tax, operating and maintenance costs. A method of life cycle cost analysis is described in the module to compare solar with non-solar systems. When the cumulative savings with the solar system is positive over the lifetime of the system, the solar system is economically viable. The largest cumulative savings among various sized collector systems is the one that is optimum for the particular installation.

MODULE 16. SOLAR SYSTEM SIZING CALCULATIONS BY TRAINEES

The participants are provided the opportunity to size a complete system. Considerable freedom is given in choosing the example problem for practice calculation, with encouragement given to choose a system for the participant's home location.

MODULE 17. COST EFFECTIVENESS OF ENERGY CONSERVATION

Energy conservation is one of the first considerations in building designs. Reduction of window area in a house consistent with sensible natural lighting is an effective energy conserving design. Thicker insulation in the walls and ceiling, particularly for new buildings, is a cost-effective energy conservation measure. Storm windows and doors, or double-pane windows will help to reduce heat losses, and reduction of heat losses will result in a smaller overall system size, and lower first cost.

MODULE 18. RETROFIT CONSIDERATIONS

Retrofit installations of solar systems is a growing concern in areas where home heating costs, using electricity, propane or fuel oils, are becoming larger each year. The costs of retrofit installations are in general larger than installations for new buildings because structural support for the collectors is an added system cost. In homes where electricity is used for heating and electricity cost is high, solar systems should be considered. Whether a solar system is economically viable to install in an existing house depends upon a great many factors, and each installation will require careful physical and economic appraisal.

MODULE 19. SCHEDULING OF SOLAR INSTALLATIONS

The scheduling of sequential and concurrent activities in installing solar systems in new buildings depends upon the type of system. Although critical path methods (CPM) are not generally needed for single home construction, a CPM is used to discuss the scheduling of both liquid and air-heating solar systems.

MODULE 20. CONSTRAINTS AND INCENTIVES

In addition to general lack of understanding of the technical and economic aspects of solar heating and cooling systems, which is a serious constraint to more wide-spread use of solar systems, there are several other constraints. Because of the newness in applying solar energy to space heating and cooling, equipment manufacturers are venturing slowly into the industry. There is lack of system performance standards and certification and generally lack of information on durability and marketability. These and other factors are however rapidly changing.

Because there is general lack of information, the financial institutions are viewing the solar industry with caution. There are however some governmental incentives being created in many states in suppressing property taxes on solar systems, and providing credit on income taxes. The federal government is accelerating efforts in research and development of better systems and demonstrating many different systems in all sectors of the country. The factors are highly variable and changing rapidly so that the information in this module will likely be outdated very quickly.

MODULE 21. BUYER'S GUIDE

In order that intelligent selection of equipment can be made, knowledge of standards, equipment warranties, performance evaluation data, building codes and their relation to solar equipment and related topics is necessary. If evaluations have been performed, their results need to be available to the supplier and user. The kinds of data required for such appraisal must be understood. The advantages and disadvantages of the main system types for a specific application are particularly important. Knowledge of the types of hardware available, their cost, and compatibility with other components in the system is essential. In addition, their involvement in building codes, and such items as safety and durability are additional guides for equipment evaluation and selection.

MODULE 22. FUTURE PROSPECTS FOR SOLAR HEATING AND COOLING SYSTEMS

Many new types of equipment for solar heating and cooling systems are undergoing research, development and testing. Some are also being demonstrated. Collectors are the largest single cost item for solar systems and much effort is being devoted to develop more efficient and at the same time less expensive collectors. Among the many prospects, there are at least four different types of evacuated tube collectors that are being tested. Concentrating collectors are also under development.

In addition to collectors, heat storage units, particularly latent heat storage materials, are being tested. A direct contact liquid-to-liquid heat exchanger and storage unit as well as methods to enhance temperature stratification in storage are being researched.

Redesign of heat pumps for heating using solar assistance has been initiated by at least one manufacturer, and solar cooling units utilizing high temperature heat from improved collectors, as well as absorber chillers using different fluids are undergoing development. Whether any or all of the new solar components will become practical depends upon many factors. Solar equipment installers should be aware of the development effort, and hopefully, much of the system developments will be directed to practical applications.

TRAINING COURSE IN
THE PRACTICAL ASPECTS OF
SIZING, INSTALLATION, AND OPERATION OF SOLAR HEATING AND COOLING SYSTEMS
FOR
RESIDENTIAL BUILDINGS

MODULE 3

INTRODUCTION TO SOLAR HEATING AND COOLING SYSTEMS

SOLAR ENERGY APPLICATIONS LABORATORY
COLORADO STATE UNIVERSITY
FORT COLLINS, COLORADO

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INTRODUCTION

The purpose of this module is to identify the types of solar heating and cooling systems that are available and in current use, and to explain the basic function of the systems and their key components. Different types of solar heating and/or cooling systems, such as active and passive systems, and air and liquid systems are explained. In addition, variations in control methods and ways of interfacing the elements of a complete system are described.

OBJECTIVE

At the end of this module, the trainee should be able to:

1. Recognize the features which distinguish active and passive solar heating systems,
2. Identify the principal characteristics of air-heating and liquid-heating solar heating and cooling systems,
3. Identify and describe the basic function of key components of a solar heating and cooling system,
4. Describe the expected performance of different types of solar systems, and
5. Recognize advantages and disadvantages of different designs of components and systems.

SOLAR HEATING AND COOLING SYSTEMS

A solar heating and/or cooling system can be defined as any system which utilizes solar energy to heat and/or cool a building, although a distinction is often made between "active" and "passive" systems. A passive system can be defined as having no moving parts, although it may involve natural circulation of fluid to the heated space. A south-facing window or a skylight which transmits sunlight can be considered a passive system if it admits more energy than it loses as heat. Another type of passive system may involve movable insulation material which reduces heat loss from solar absorber surfaces when there is no sunshine. In contrast to a passive system, an active system involves hardware to collect solar energy, store heat, and distribute the heat to the rooms in a building.

Passive systems are not included in this course because there is very little known about the design and performance of such systems. The emphasis in this course is on active solar systems which provide controlled collection and distribution of solar heat. Active systems can be integrated directly into conventional HVAC systems in buildings.

Figure 3-1 is a schematic drawing of an active solar heating and cooling system, representative of those available today. The key elements are a solar collector, a heat storage unit, an auxiliary furnace, a heat-transfer circuit (pumps, blowers, etc.), a method of delivering heat to the house, and a cooling machine for space cooling. In addition, many solar systems include facilities for providing solar heat to the domestic hot water system.

Operationally, the solar collector intercepts solar radiation, converts it to heat and, utilizing some heat-transfer fluid, transfers the collected energy to a thermal storage unit (or, in some cases, directly to the heating load). The thermal storage unit is an essential element because it provides for the use of solar generated heat to be available during periods of low solar radiation and at night. In general, the solar collector and thermal storage unit can operate independently of

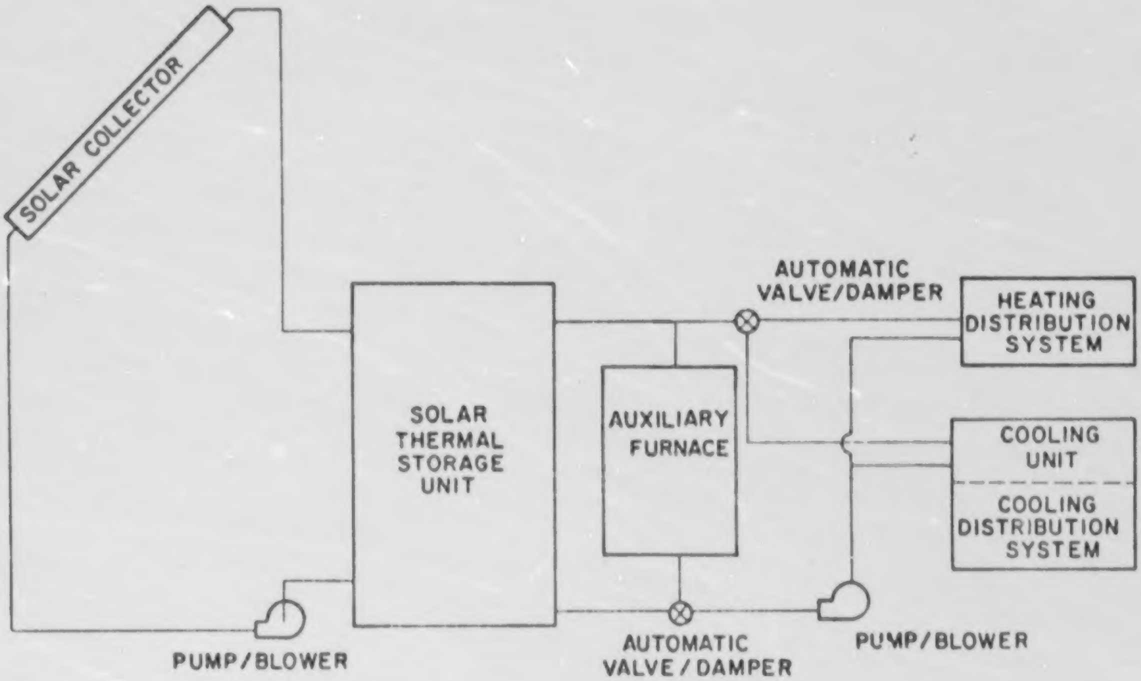

SOLAR COLLECTOR
AUTOMATIC VALVE/DAMPER
HEATING DISTRIBUTION SYSTEM
SOLAR THERMAL STORAGE UNIT
AUXILIARY FURNACE
COOLING UNIT
COOLING DISTRIBUTION SYSTEM
PUMP/BLOWER
AUTOMATIC VALVE/DAMPER
PUMP/BLOWER

Figure 3-1. Schematic Drawing of a Solar Heating and Cooling System

any heating or cooling requirement, and can be collecting and storing solar energy whenever there is sufficient incident solar radiation.

An auxiliary furnace is required as a back up to the heating/cooling system for periods of the year when the solar collector/thermal storage subsystem is unable to meet the heating/cooling demands. While the solar collector could be sized large enough to provide the full heating load throughout the year, this is not as economical as an auxiliary assisted system. It is preferable to have an auxiliary furnace or boiler capable of meeting the full heating/cooling demand (at design conditions) and use this auxiliary during periods of high heating/cooling demands and low solar availability.

Heat delivery to the building can be accomplished in several ways. In an air system the solar heated air can be taken directly from either the solar collector or the thermal storage unit and delivered to the building by utilizing a blower and duct distribution. In a liquid system a liquid-to-air heat exchanger can be used to provide heat to a central air distribution system, or the liquid can be piped directly to the heated space, where separate fan coil units can be used to heat the building.

A number of different methods can be used for cooling. These include absorption cooling units (both lithium-bromide and ammonia-water systems), Rankine cycle vapor-compression, and others. (However, only the lithium-bromide absorption unit is commercially available and it has been used only in experimental installations.) Alternatively, a heat pump might be utilized as a conventional cooling unit (powered by electricity) and used as the auxiliary for the solar space heating system.

Figure 3-2 is a typical schematic drawing showing the arrangement of components for utilizing solar heat in a domestic hot water system (DHW). Solar energy from a collector or a thermal storage unit is used to preheat the domestic hot water available from the cold water main. As hot water is used in the building, the preheated water replaces the hot water taken out of the auxiliary hot water tank. Conventional fuels such as gas or electricity are used to boost the temperature of the preheated water to the desired temperature (e.g., 140°F), and/or to maintain the temperature of the water remaining in the auxiliary tank at the desired temperature. During the summer a solar thermal storage unit provided as part of the heating and cooling system can normally meet one hundred percent of the domestic hot water load.

In addition to the components of conventional heating and/or cooling systems normally required to meet the heating and cooling loads, a solar

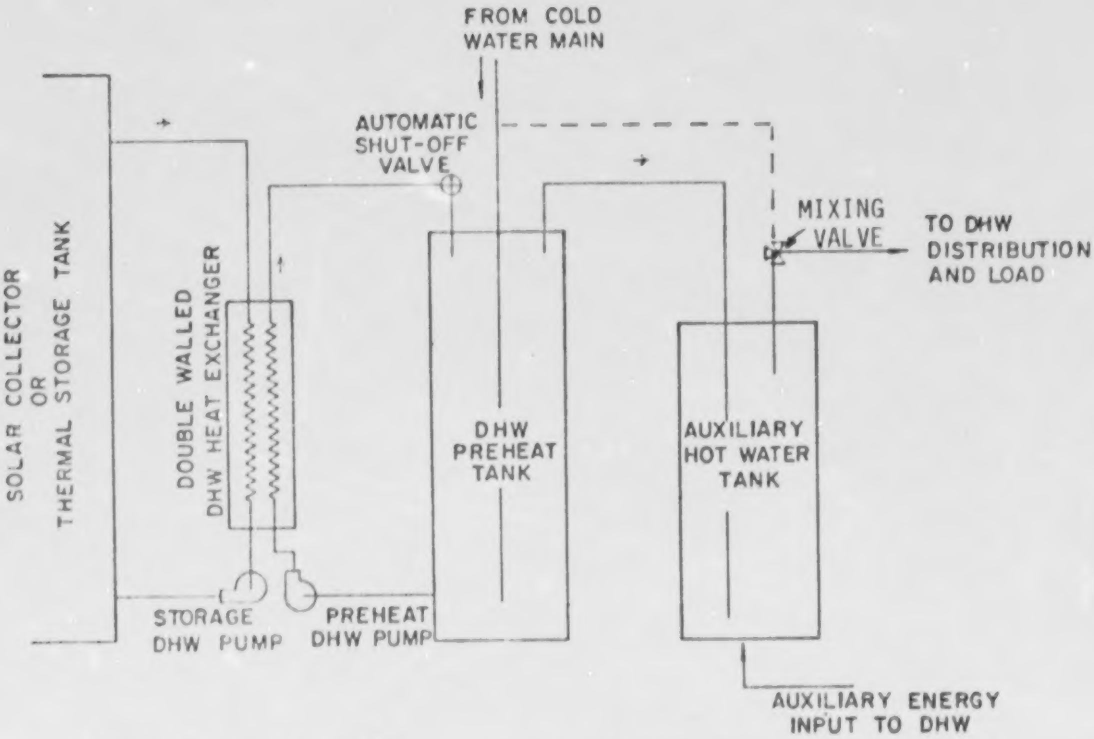

FROM COLD WATER MAIN
AUTOMATIC SHUT-OFF VALVE
MIXING VALVE
TO DHW DISTRIBUTION AND LOAD
SOLAR COLLECTOR OR THERMAL STORAGE TANK
DOUBLE WALLED DHW HEAT EXCHANGER
DHW PREHEAT TANK
AUXILIARY HOT WATER TANK
STORAGE DHW PUMP
PREHEAT DHW PUMP
AUXILIARY ENERGY INPUT TO DHW

Figure 3-2. Schematic Arrangement of a Domestic Hot Water (DHW) Subsystem

system requires the addition of solar collectors, thermal storage units, DHW preheat tanks, some additional plumbing/sheet metal work, and more extensive control systems. The emphasis of this course will be to provide the details of these additions to the conventional systems and the interfaces between the solar subsystem and the conventional HVAC components. Of the additional solar components, the most important is the solar collector.

SOLAR COLLECTORS

A solar collector is a device to convert incident solar radiation to useful energy, usually in the form of heated air or heated liquid. Figures 3-3 and 3-4 show examples of liquid-type and air-type solar collectors used in solar heating and cooling systems.

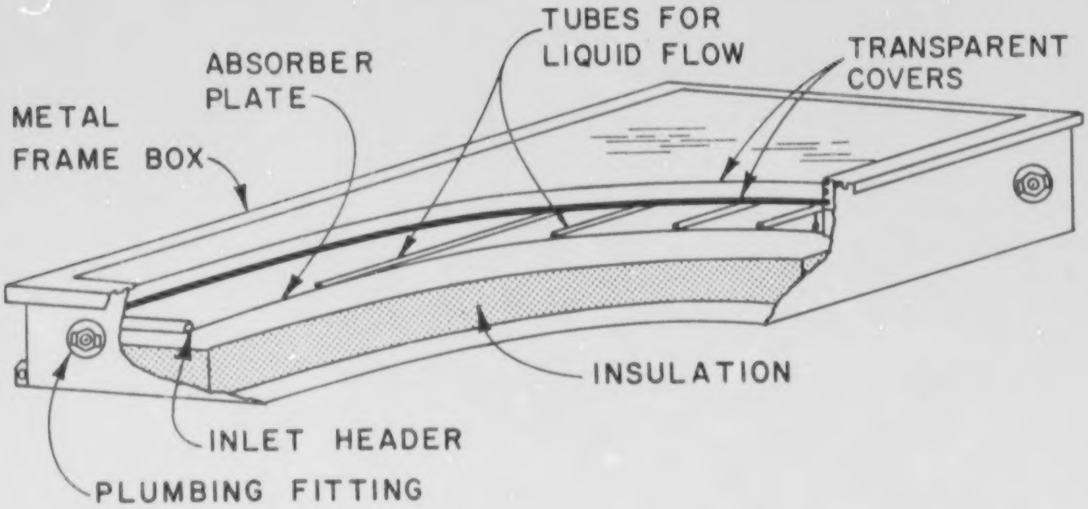
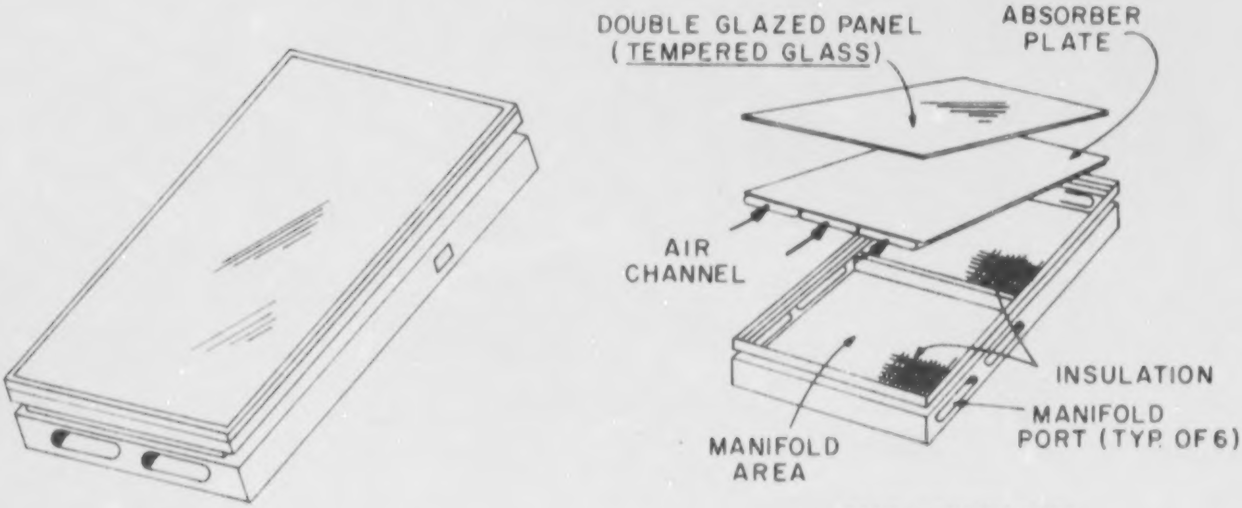

TUBES FOR
LIQUID FLOW
TRANSPARENT
COVERS
ABSORBER
PLATE
METAL
FRAME BOX
INSULATION
INLET HEADER
PLUMBING FITTING

Figure 3-3. Solar Collector Schematic (Liquid)


DOUBLE GLAZED PANEL
(TEMPERED GLASS)
ABSORBER
PLATE
AIR
CHANNEL
INSULATION
MANIFOLD
PORT (TYP. OF 6)
MANIFOLD
AREA

COLLECTOR PANEL

PANEL DIMENSIONS:
3'-0" W x 6'-6" L x 7.25" H

NOTE: AIR FLOWS THRU THE CHANNELS BENEATH THE ABSORBER PLATE

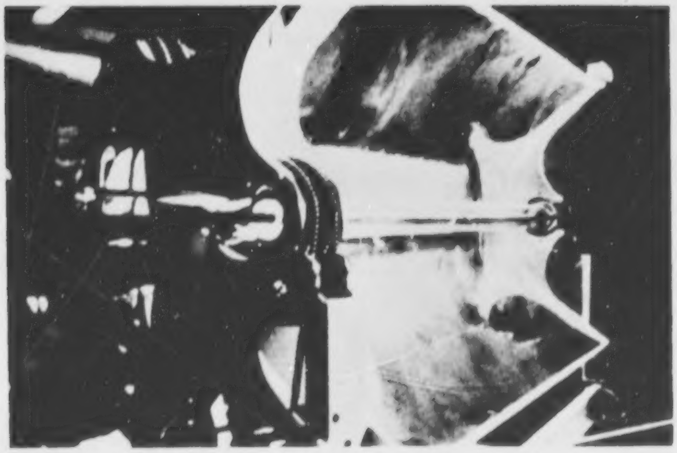
Figure 3-4. Solar Air Heating Collector

Each collector consists of an absorber plate (commonly a blackened metal surface) which absorbs the incident solar radiation and converts the solar energy to heat. The heat in the absorber plate is transferred to an appropriate heat transfer fluid which passes through the absorber plate and delivers the heat to another part of the system. In the process of collecting energy, the heated absorber plate will tend to lose heat to the surroundings. The solar collector components other than the absorber plate are therefore designed to reduce these heat losses from the collector.

Heat may be lost from the absorber plate by radiation, conduction, and/or convection. Insulation beneath the absorber and the transparent covers above reduce the heat loss from all three methods. Glass covers, for example, are opaque to the thermal radiation emitted from the absorber plate and also reduce convection losses due to air movement across the absorber. The air space between the absorber plate and cover acts to reduce conduction losses between these two components.

The collectors in Figure 3-3 and 3-4 are flat-plate solar collectors and represent commercially available types. They are called flat-plate collectors to distinguish them from concentrating collectors, which gather solar radiation over a large aperture area and focus the radiation onto a smaller absorber area. Two examples of concentrating solar collectors of the reflecting type are shown in Figure 3-5, and a transmitting lens type is shown in Module 22, Figure 22-3. The purpose of a concentrating collector is to obtain fluid at a higher temperature than possible in a flat-plate type, even though the quantity of heat gained is nearly the same as for a flat-plate collector with the same aperture area.

A technical disadvantage of a concentrating solar collector is that only the direct solar radiation can be used. Diffuse solar radiation,



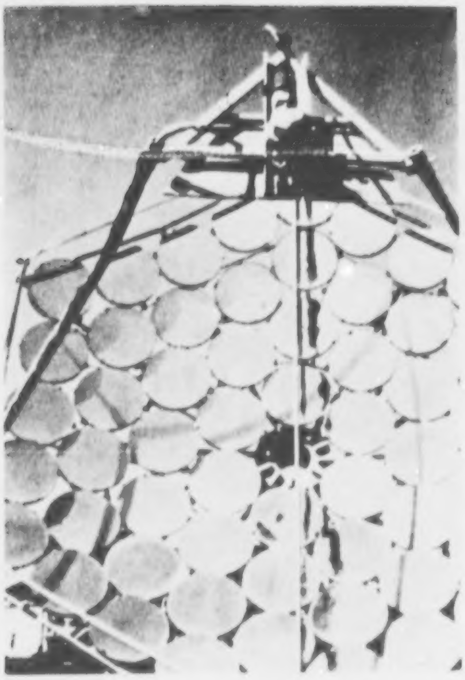


Figure 3-5. Solar Concentrating Collectors

resulting from reflections from the earth and sky, cannot be focused (see Figure 3-6). In addition, the concentrating solar collector must track the sun throughout the day for greatest effectiveness. The expense of construction, operation, and maintenance of a rotating, tracking collector is usually much too high for the use of this form of solar energy collector in solar heating and/or cooling systems.

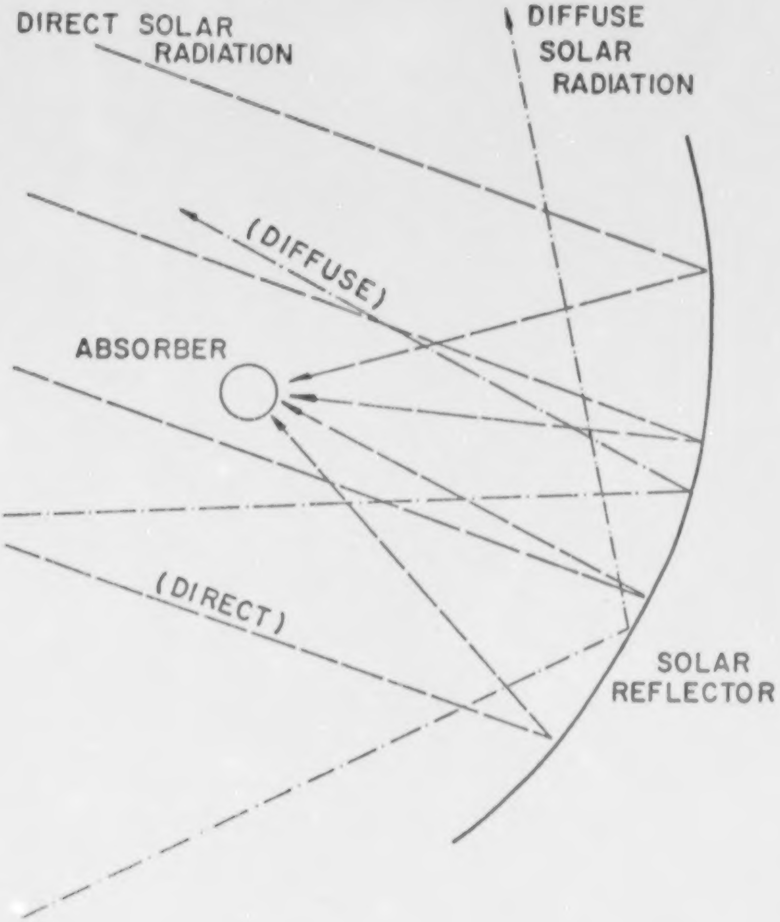

DIRECT SOLAR RADIATION
DIFFUSE SOLAR RADIATION
(DIFFUSE)
ABSORBER
(DIRECT)
SOLAR REFLECTOR

Figure 3-6. Direct and Diffuse Radiation on a Solar Concentrator

A rather distinct type of flat-plate collector, described in Module 22, comprises a glass tube surrounding a flat or cylindrical absorbing surface. As shown in Figures 22-1 and 22-2, a high vacuum inside the tube minimizes heat losses from these collectors. There is no concentration of radiation in this type, but delivery temperatures may be considerably higher than usually obtained in typical flat collectors.

THERMAL STORAGE UNITS

Because of variations in solar radiation and atmospheric temperature and the resulting non-correspondence between available solar heating and heating load demand, some form of energy storage is required. This energy storage requirement is most economically provided for by some form of thermal storage, i.e., storage of heat (or cool) for heating and cooling systems. The types of thermal storage units which might be utilized are quite extensive; but, because of simplicity and economy, most commercial solar systems utilize either hot water storage for the liquid system or pebble-bed storage for air systems.

It is technically possible to store heat in scrap metal, eutectic salts, waxes, ceramic bricks, etc. Scrap metal or bricks store sensible heat and could be used in place of a pebble-bed unit. Generally, however, rocks are the least expensive material. Chemical storage using several types of chemical compounds and waxes can store heat by using the latent heat of phase changes between a solid and liquid, rather than sensible heat storage, such as raising the temperature of water. Because the heat required to melt a solid and subsequently delivered when the molten material resolidifies is considerably greater than the heat involved in changing the temperature of an equal mass of water or rocks fifty degrees or so, a phase-change heat storage unit can be much smaller than the other types. However, because of technical difficulties and economic disadvantages, phase-change storage materials are not ready for practical use in solar heating and cooling systems. For our purposes we will concentrate on hot water and pebble-bed thermal storage units.

OPERATING MODES - AIR SYSTEMS

The collection and storage of solar-generated heat can be accomplished in a variety of ways. An example of a solar heating system is shown in Figure 3-7. The components of this typical unit include: (1) a fixed solar air-heating collector have a flat absorber and heat exchanger plate; (2) a pebble-bed heat storage unit to and from which heat is transferred by circulating air through the bed; (3) a control unit which includes the sensors and control logic necessary to automatically maintain comfort conditions at all times; (4) an air handling

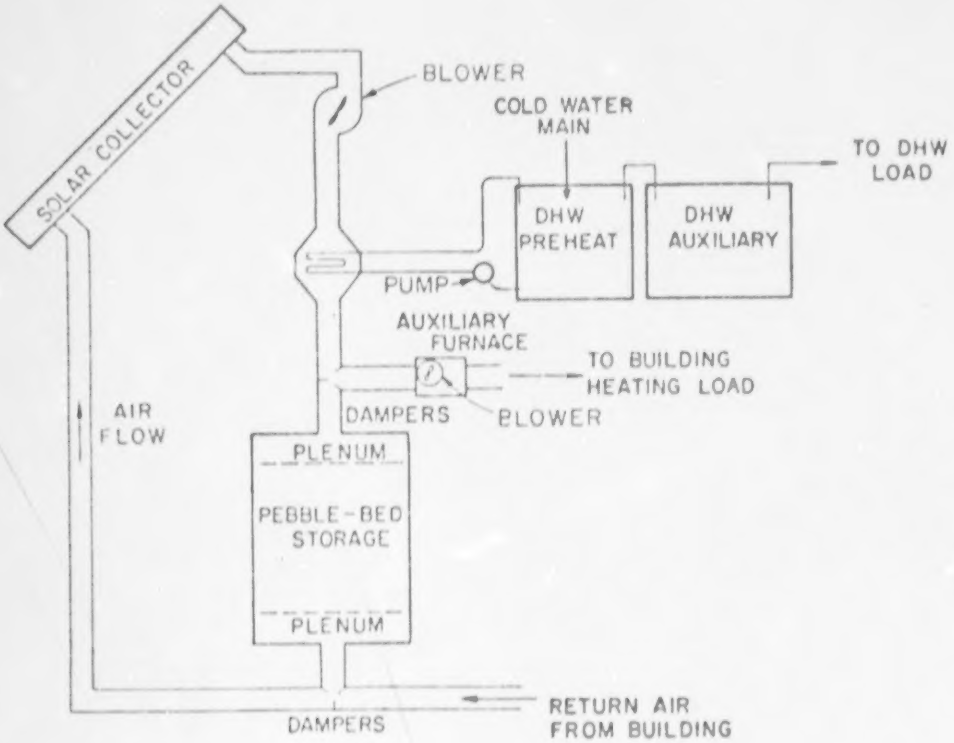

SOLAR COLLECTOR
BLOWER
COLD WATER MAIN
TO DHW LOAD
DHW PREHEAT
DHW AUXILIARY
PUMP
AUXILIARY FURNACE
TO BUILDING HEATING LOAD
DAMPERS
BLOWER
AIR FLOW
PLENUM
PEBBLE-BED STORAGE
PLENUM
RETURN AIR FROM BUILDING
DAMPERS

Figure 3-7. Solar Air Heating System

module comprising automatic dampers, filters, and blower(s); (5) a solar hot water heater consisting of an air-to-water heat exchanger and a preheat storage tank connected to an auxiliary hot water heater; and (6) an auxiliary heating unit (usually a warm-air furnace) to provide one hundred percent back-up space heating when storage temperatures are insufficient to meet demands or when the solar system is not operating.

In the air heating system the collector absorbs solar radiation and converts it to heated air for space heating. Circulation is from the solar system to the building in the same manner as in most modern warm air heating systems. Air is circulated from one end of the collector to the other, its temperature normally rising from 70 degrees to 130 to 150 degrees during the mid-part of the day. The building is heated directly from the collector whenever heating is needed during sunny periods, as shown in Figure 3-8. Cool air from the building is returned to the collector for reheating.

The heat storage unit utilizes the heat exchange and heat storage characteristics of dry pebbles, the most practical storage medium for use with air heating collectors. When heat is not needed in the building, solar heated air is routed through the storage unit as in Figure 3-9, thereby heating the pebbles; the cool air, usually at 70°F, returns to the collector for reheating. Temperature stratification in the storage unit assures maximum heat recovery from the solar air collector. In the evening and night-time hours, heat is delivered to the rooms by circulating air from the building through the pebble-bed, as in Figure 3-10. Because of temperature stratification in the storage unit, this mode provides heat to the rooms at the highest available temperature. The system automatically provides auxiliary heating from fuel or electricity when solar heat is not available from either the collector or storage.

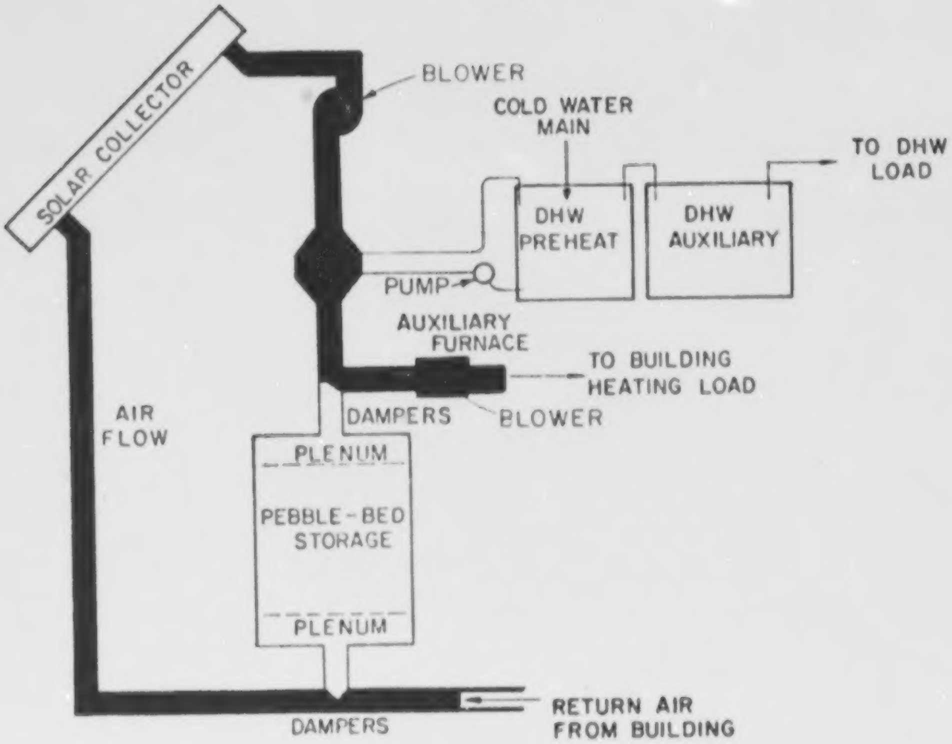

SOLAR COLLECTOR
BLOWER
COLD WATER MAIN
TO DHW LOAD
DHW PREHEAT
DHW AUXILIARY
PUMP
AUXILIARY FURNACE
TO BUILDING HEATING LOAD
DAMPERS
BLOWER
AIR FLOW
PLENUM
PEBBLE-BED STORAGE
PLENUM
RETURN AIR FROM BUILDING
DAMPERS

Figure 3-8. Heating from Collector

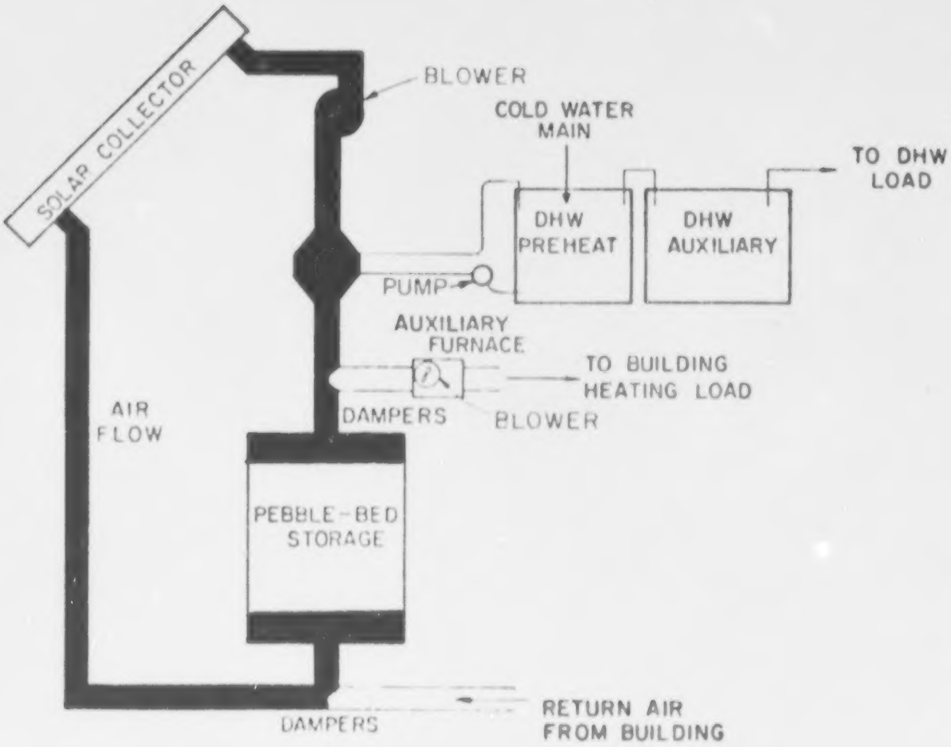

SOLAR COLLECTOR
BLOWER
COLD WATER MAIN
TO DHW LOAD
DHW PREHEAT
DHW AUXILIARY
PUMP
AUXILIARY FURNACE
TO BUILDING HEATING LOAD
DAMPERS
BLOWER
AIR FLOW
PEBBLE-BED STORAGE
RETURN AIR FROM BUILDING
DAMPERS

Figure 3-9. Storing Heat from Collector

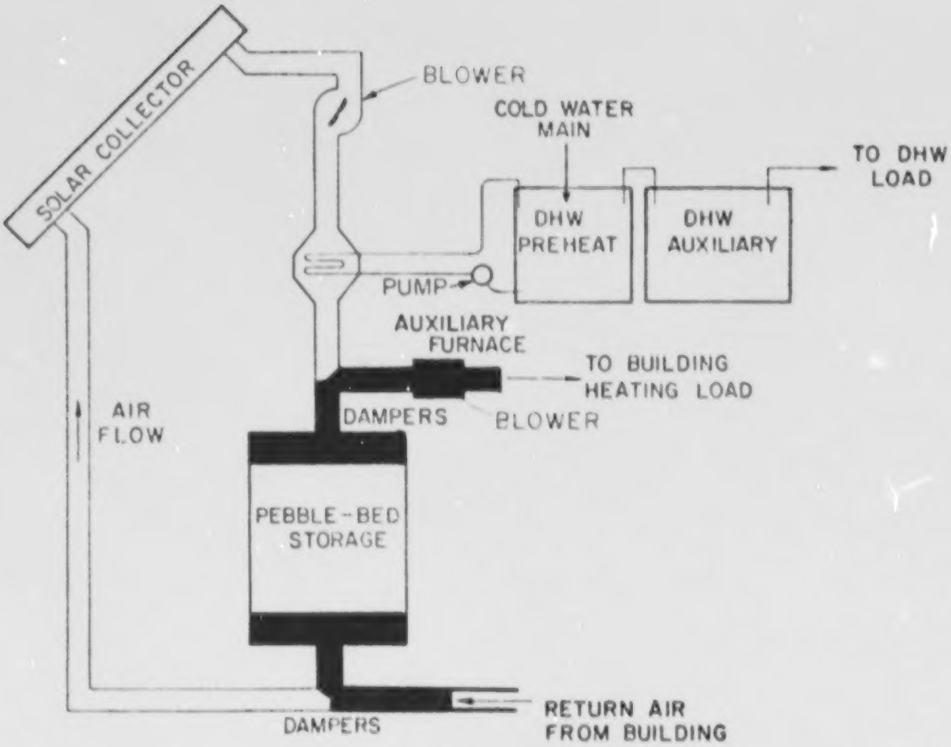

SOLAR COLLECTOR
BLOWER
COLD WATER MAIN
TO DHW LOAD
DHW PREHEAT
DHW AUXILIARY
PUMP
AUXILIARY FURNACE
TO BUILDING HEATING LOAD
DAMPERS
BLOWER
AIR FLOW
PEBBLE-BED STORAGE
RETURN AIR FROM BUILDING
DAMPERS

Figure 3-10. Heating from Storage

Domestic hot water can be made available by inserting a hot water heat exchanger in the hot air duct from the collectors (Figure 3-11). Thus solar energy can provide preheated water whenever the collector is in operation.

At the present time, no cooling equipment is commercially available for operation by means of solar heated air.

OPERATING MODES - LIQUID SYSTEMS

The connection between the solar collector and the thermal storage unit may be more complicated in a liquid system than in an air system. The complication is due to factors such as corrosion, freezing, and the

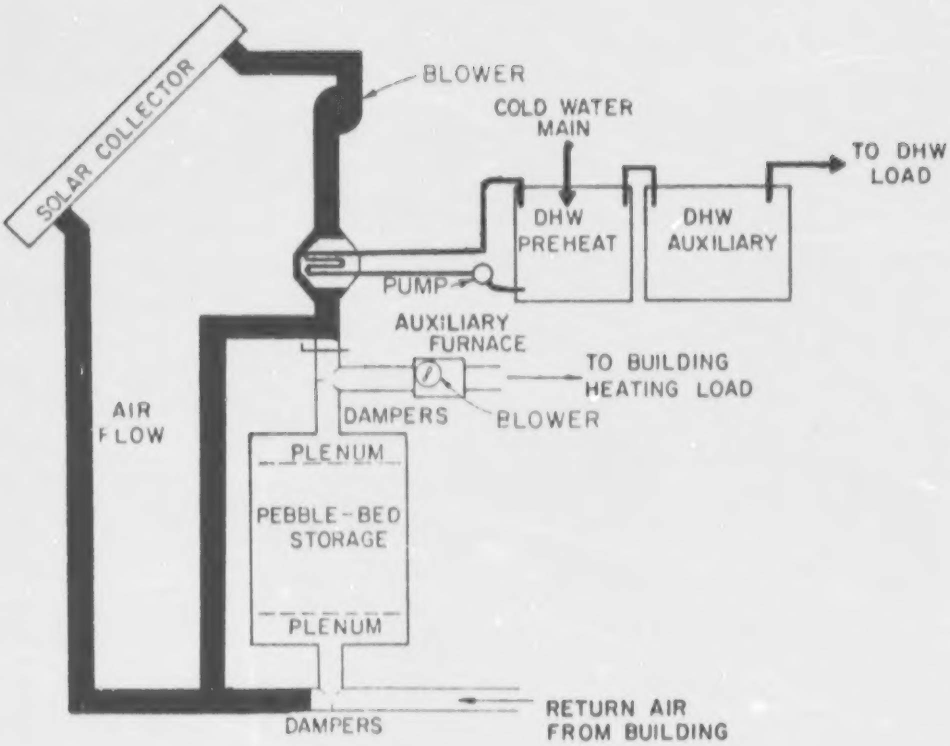

SOLAR COLLECTOR
BLOWER
COLD WATER MAIN
TO DHW LOAD
DHW PREHEAT
DHW AUXILIARY
PUMP
AUXILIARY FURNACE
TO BUILDING HEATING LOAD
AIR FLOW
DAMPERS
BLOWER
PLENUM
PEBBLE-BED STORAGE
PLENUM
RETURN AIR FROM BUILDING
DAMPERS

Figure 3-11. Solar Heating of Domestic Hot Water

use of different fluids in different loops. In nearly all practical liquid systems, heat is stored as hot water in a well-insulated tank.

If water is used in the solar collectors in a cold climate, some freeze protection method must be used. The most direct method is to allow the collector to drain into the storage tank whenever the pump turns off. One version of this method is shown in Figure 3-12, where water is the storage medium as well. When the solar intensity is sufficient for heat collection, a pump circulates water through the collectors and the thermal storage unit. When the pump shuts off, the water in the collector drains into the storage tank. A vent is provided at the top of the collector so that air can enter the collector tubes as water drains out.

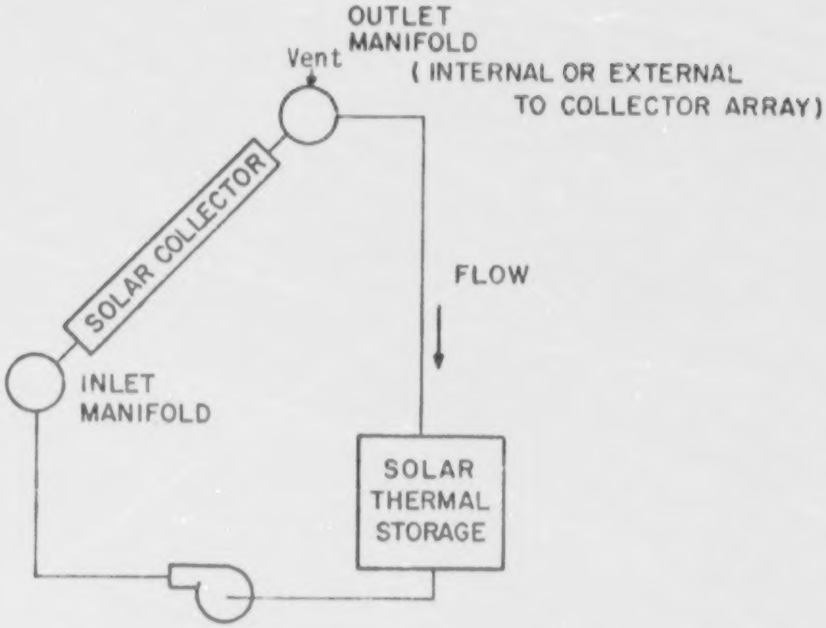

OUTLET
MANIFOLD
(INTERNAL OR EXTERNAL
TO COLLECTOR ARRAY)
Vent
SOLAR COLLECTOR
FLOW
INLET
MANIFOLD
SOLAR
THERMAL
STORAGE

Figure 3-12. Solar Collector Subsystem Schematic
(Liquid System)

Figure 3-13 shows an alternate method wherein ethylene glycol (antifreeze) is used with water in the collector loop. To avoid the cost of a large quantity of glycol in the storage liquid (approximately 250 gallons or more of antifreeze), a heat exchanger is inserted between the collector and storage tank. An additional pump is usually required, depending on the location and type of heat exchanger.

The advantage of this design is that there is no risk of freezing (and damage) from improper collector draining or venting; nor from corrosion caused by the alternating exposure of the collector tubes to water and air. The possibility of corrosion and freezing (in Figure 3-12) can thus be compared with the cost penalty of the exchanger, pump, and additional piping for the design in Figure 3-13.

A more significant factor is the "driving temperature" across the heat exchanger. Typically the collector fluid operates 10 to 15 degrees

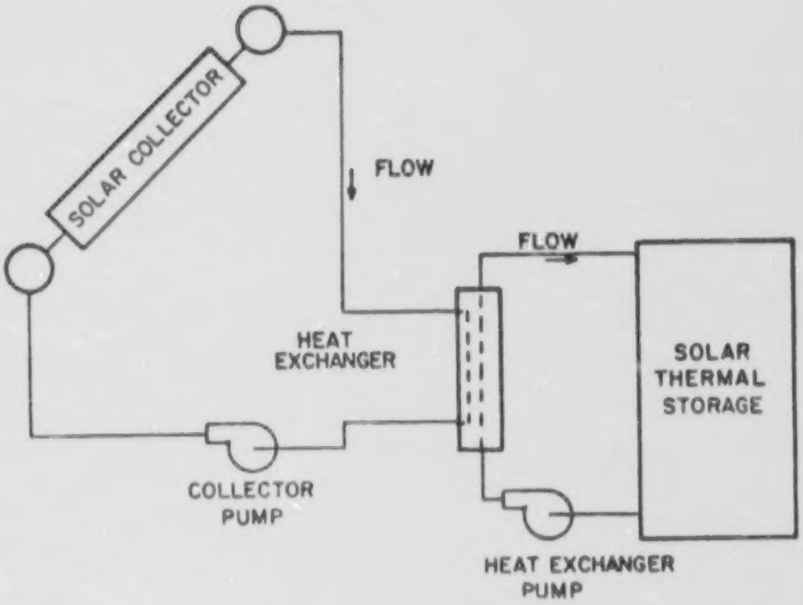

SOLAR COLLECTOR
FLOW
FLOW
HEAT EXCHANGER
SOLAR THERMAL STORAGE
COLLECTOR PUMP
HEAT EXCHANGER PUMP

Figure 3-13. Collector Loop with Heat Exchanger

hotter than storage. This higher temperature results in a decrease in collector efficiency. These factors will be discussed in more detail in the section on solar collectors.

Another important consideration involving the system in Figure 3-13 is the effect of a power failure. In this event, circulation ceases and, usually in a few minutes, the collector fluid begins to boil. A pressure relief mechanism should always be included in the system so that overpressure will not occur and the steam can escape. The problem occurs when the power returns and there is insufficient fluid in the collector loop to prime the pump and achieve circulation. Figure 3-14 is designed to partially alleviate this problem by providing make-up water (either from a tank or directly from the water supply), but loss of antifreeze may require manual addition.

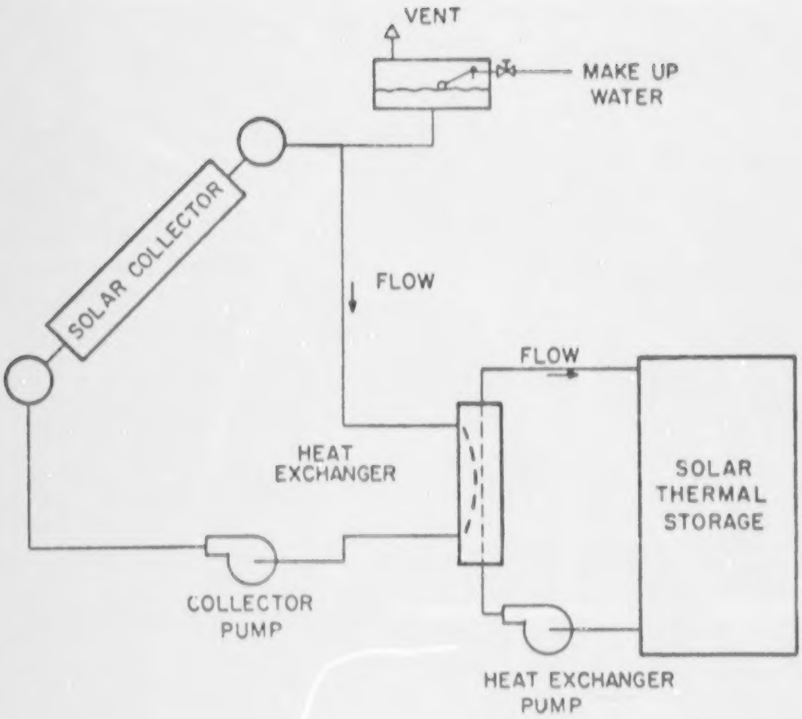

VENT
MAKE UP WATER
SOLAR COLLECTOR
FLOW
FLOW
HEAT EXCHANGER
SOLAR THERMAL STORAGE
COLLECTOR PUMP
HEAT EXCHANGER PUMP

Figure 3-14. Collector Loop with Make-Up Water Supply

SPACE HEATING AND COOLING - DISTRIBUTION

Distribution of solar heated and cooled air in a building can be the same as in any other commercial heating/cooling system. In "hydronic" types, water can be piped from storage to coils imbedded in floors or ceilings (radiant heating) or to "radiators" or fan-coil units in individual rooms. The operating temperature requirements of baseboard hot water heating are usually too high for use with a solar system, unless dual baseboard circuits are provided, one for the solar heated water and one for conventional heating. But most solar heating systems employ central forced air distribution. Hot water from the solar storage tank is piped to a heating coil (Figure 3-15) in which circulating air picks

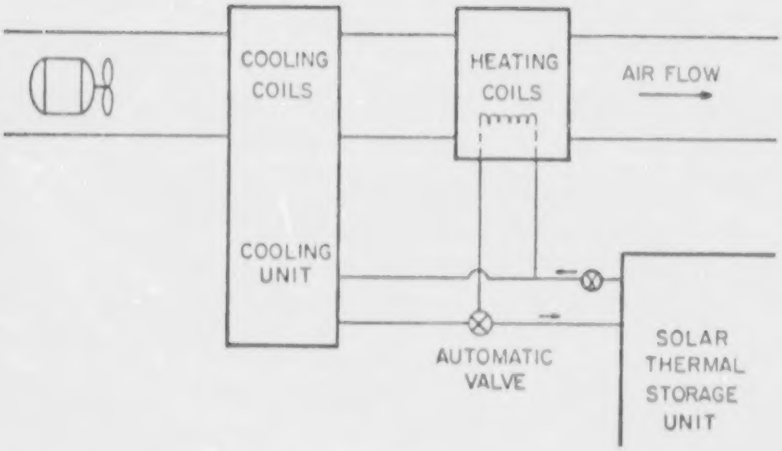


Figure 3-15. Solar Heat to Distribution System

up the heat for delivery to the rooms. For cooling, hot water from the solar storage tank can be piped to an air conditioner, where it provides the energy to operate a lithium bromide absorption cooling unit. An evaporator coil in the air duct cools and dehumidifies the circulating air.

Besides heating and cooling the house, solar energy may be used to provide most of the domestic hot water needs (Figure 3-2). Water from a cold water main enters the preheat tank from which it is circulated through a heat exchanger, where it is heated by hot water from the solar storage tank. When a hot water faucet is opened, water from the preheat tank enters a conventional gas or electric hot water heater where the water temperature can be increased (if needed) before passing to the distribution piping.

AUXILIARY UNITS

During cloudy periods and in midwinter, the solar system may not be able to meet all of the heating or cooling needs of the building. With a liquid system, a conventional hot water boiler may be provided to supply part or all of the heating or cooling requirements during these periods. If the temperature in the solar storage tank drops below a preset point (e.g., 100°F for heating, 170°F for cooling), the auxiliary boiler automatically supplies hot water to the heating coils or the air conditioning unit.

A warm air furnace may be used for supplying auxiliary heat (not usable for cooling), if the building is provided with a warm air heating system. This form of auxiliary heat is nearly always used with air collectors and pebble storage, and is often the choice when liquid collectors and liquid-to-air heat exchanges are employed. The furnace may also be replaced by an air-to-air heat pump in air systems.

In a solar heating and cooling system, the auxiliary unit supplies energy for both the heating and cooling functions, and operates as a "replacement"; if solar heat is unavailable (either from the collector or from storage), the auxiliary delivers heat for the entire load. Heating or cooling is accomplished either with solar or auxiliary energy (Figure 3-16-a). An alternative is to use the auxiliary to "boost" the temperature of the solar heated fluid (air or water) as in Figure 3-16-b. This arrangement is ideal for an air distribution system but should not be used in a water loop.

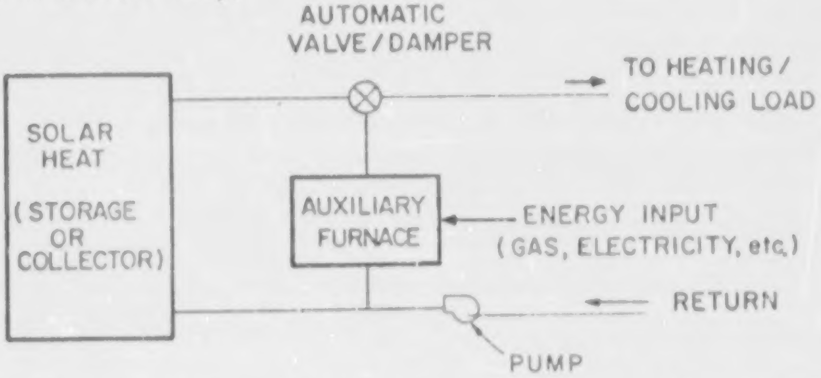


Figure 3-16-a. Typical Liquid System Use of Auxiliary

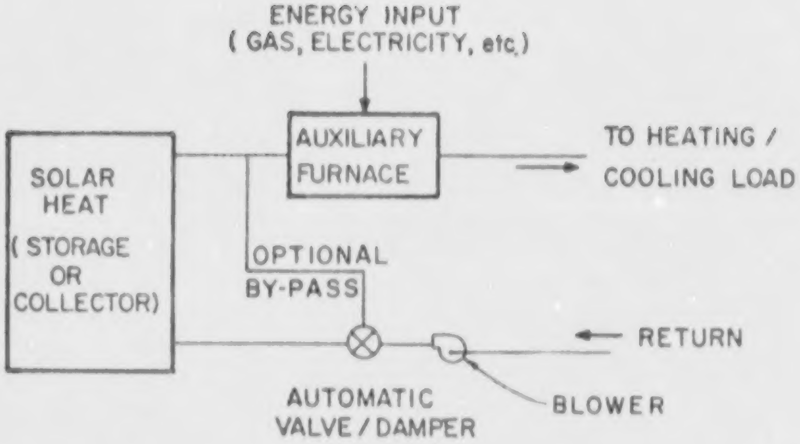

ENERGY INPUT
(GAS, ELECTRICITY, etc.)
AUXILIARY FURNACE
SOLAR HEAT
(STORAGE OR COLLECTOR)
TO HEATING / COOLING LOAD
OPTIONAL BY-PASS
RETURN
AUTOMATIC VALVE / DAMPER
BLOWER

Figure 3-16-b. Typical Air System Use of Auxiliary

AUTOMATIC CONTROLS

To control the temperature in a conventionally heated home, the homeowner needs only to set the thermostat. The same is true for a well designed solar heating and/or cooling system. However, the controls for solar heating and cooling are necessarily more complex than in a conventional system, because they must control collector and storage pumps or blowers and automatic valves or dampers in addition to the usual functions. An example of a solar control schematic for a domestic hot water system is shown in Figure 3-17.

The differential thermostat senses the difference in temperature at collector outlet and the storage tank. When this difference is more than a few degrees, the circulating pump is operated. The high set thermostat prevents too high a temperature in the preheat tank by interrupting power to the collector pump. A pressure relief valve protects the system from excessive pressure, which might otherwise develop if there is no circulation through the collector during a sunny period.

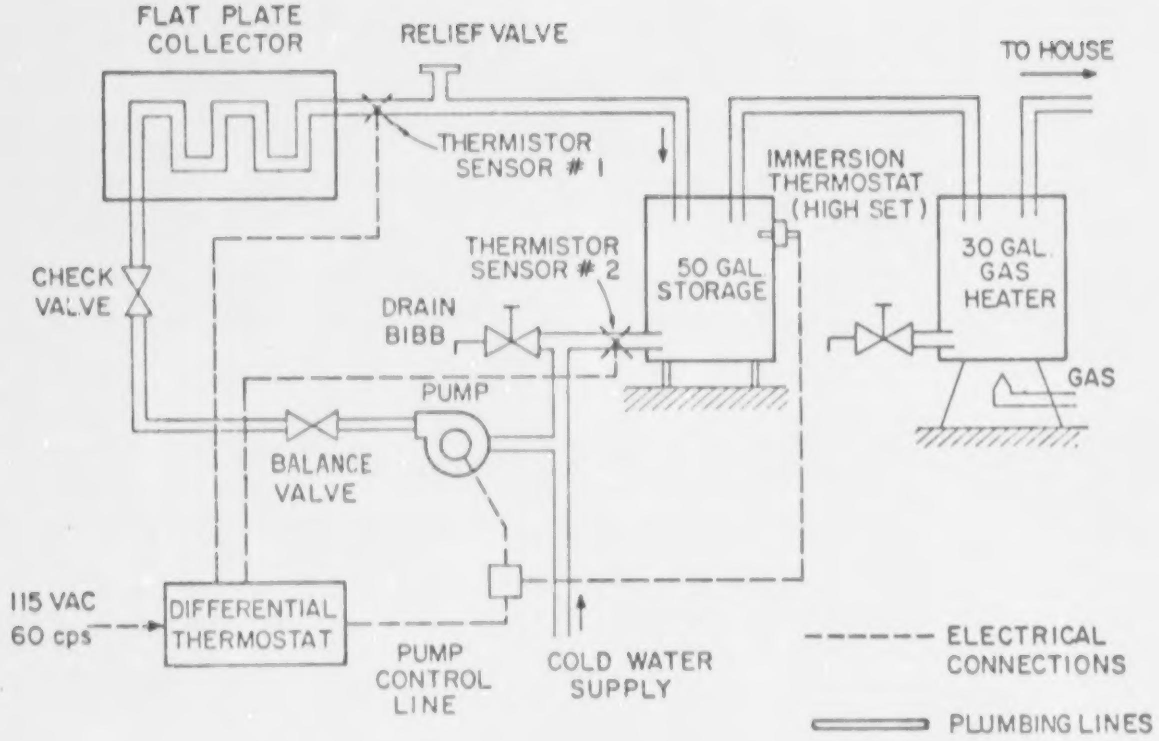

FLAT PLATE COLLECTOR
RELIEF VALVE
TO HOUSE
THERMISTOR SENSOR # 1
IMMERSION THERMOSTAT (HIGH SET)
THERMISTOR SENSOR # 2
50 GAL STORAGE
30 GAL. GAS HEATER
CHECK VALVE
DRAIN BIBB
GAS
PUMP
BALANCE VALVE
115 VAC 60 cps
DIFFERENTIAL THERMOSTAT
PUMP CONTROL LINE
COLD WATER SUPPLY
ELECTRICAL CONNECTIONS
PLUMBING LINES

Figure 3-17. Typical Solar Hot Water Control System

Numerous controllers for solar space heating systems are commercially available, and many varieties of control circuits and methods are being used. Design of control systems requires directions from the manufacturers of the control components and experience in their proper integration and adjustment.

TRAINING COURSE IN
THE PRACTICAL ASPECTS OF
SIZING, INSTALLATION, AND OPERATION OF SOLAR HEATING AND COOLING SYSTEMS
FOR
RESIDENTIAL BUILDINGS

MODULE 4

SOLAR RADIATION

SOLAR ENERGY APPLICATIONS LABORATORY
COLORADO STATE UNIVERSITY
FORT COLLINS, COLORADO

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GLOSSARY OF TERMS

beam radiation	See "direct radiation"
Btu	British Thermal Unit - the heat required to raise one pound of water one degree Fahrenheit
calorie	The heat required to raise one gram of water one degree Centigrade
diffuse radiation	Radiation that has been scattered in passing through the atmosphere
direct radiation	Radiation that has not been scattered in passing through the atmosphere
infrared light	Light of low energy, abbreviated "IR"
insolation	The solar radiation that reaches earth
latitude	The distance, measured in degrees, north and south from the equator
northern hemisphere	The half of the Earth north of the equator
ozone layer	A layer in the upper atmosphere comprised primarily of the gas ozone (O_3)
ultraviolet light	Light of high energy, abbreviated "UV"
visible light	Light of intermediate energy

INTRODUCTION

Solar energy starts, of course, with the sun. The sun is a huge nuclear fusion reactor located at an average distance of 93 million miles from earth. It has a surface temperature of about 10,800°F, and gives off energy continuously in the form of radiation. The use of the energy which reaches earth for heating and cooling is what this course is all about. In this module you will learn about the way the energy given off by the sun is altered before it reaches the earth and the amount of energy that reaches earth.

OBJECTIVE

The objective of the trainee will be to recognize the factors which affect the availability of solar radiation at the earth's surface. At the end of this module the trainee should be able to:

1. Recognize the effect on energy reaching a collector due to clouds, dust and atmospheric pollutants, shading (trees, buildings, etc.), collector orientation, and collector tilt
2. Differentiate between beam and diffuse radiation
3. Recognize the various units used to measure solar energy
4. Given conversion factors, convert solar radiation from one set of units to another
5. Recognize the magnitude of solar radiation available
6. Describe seasonal variations in solar radiation
7. Describe daily variations in solar radiation
8. Locate sources of solar data
9. Select the data needed for planning a solar system.

SOLAR RADIATION

UNITS

The intensity of solar energy is found expressed in several different units. In this course only one unit will be used, Btu/ft^2. However, you may often find other units when looking for solar data, so it is worthwhile to learn to recognize these units and to be able to convert from one unit to another. Units commonly found are listed in Table 4-1.

Table 4-1

Energy Units

Abbreviation	Unit
Energy Density	
Btu/ft^2	British Thermal Units per square foot
KJ/m^2	Kilojoules per square meter
Langley (cal/cm^2)	calories per square centimeter
Power	
Btu/ft^2·hr	British Thermal Units per square foot per hour
KJ/m^2·hr	Kilojoules per square meter per hour
Langley/min	calories per square centimeter per minute
W/m^2	Watts per square meter

Table 4-2 gives conversion factors from one set of units to another. An example will show the use of this table. The Climatic Atlas of the United States lists the annual average daily solar radiation for Boulder, Colorado as 367 Langleys per day. To convert this to Btu/ft^2, multiply by the conversion factor from Table 4-2 for Langleys to Btu/ft^2, 3.69:

$$\underset{\text{(Langleys/day)}}{367} \times 3.69 = \underset{\text{(Btu/ft}^2\text{ day)}}{1354}$$

Table 4-2

Energy Conversion Factors

To Convert into Btu/ft^2		To Convert into $Btu/ft^2 \cdot hr$	
Multiply	By	Multiply	By
Langleys	3.69	Langleys/min	221
KJ/m^2	.088	$KJ/m^2 \cdot hr$	.088
		W/m^2	.316

SOLAR INTENSITY

The intensity of the sun's energy output varies with distance from the sun. At the average earth-sun distance, the intensity of solar energy has been determined to be 1.940 Langleys/min, or 428 $Btu/ft^2 \cdot hr$ with a variability of about three percent. The value of 428 $Btu/ft^2 \cdot hr$ is called the "solar constant". Due to the earth's elliptical orbit around the sun, the distance from the earth to the sun changes during the year so that the energy reaching the outer atmosphere of the earth varies from 410 to 440 $Btu/ft^2 \cdot hr$. While there is some variability in the amount of solar energy that reaches the outer atmosphere around earth, there are very large variations in the amount of solar energy available at a particular location on the earth's surface. The surface radiation is what is of interest to us, and the radiation intensity will vary considerably with latitude, season of the year, and local weather conditions.

THE SOLAR SPECTRUM

The radiation from the sun can be separated into three major energy regions. The high frequency energy in the radiation spectrum is labeled "ultraviolet" or "UV" and is detected by the human body in terms of its effect - primarily sunburn. The medium frequency energy radiation band in the solar spectrum is the visible band. The low frequency radiation band is the "infrared" or "IR" region. The greatest concentration of solar energy is in the visible band, and solar collectors must be designed to intercept this portion of the solar spectrum.

ENERGY REACHING EARTH

The energy reaching earth is reduced from the "outer space" intensity. There are a number of processes that occur in the atmosphere that cause this reduction. Some of the energy is reflected back into outer space by the top of the atmosphere, much as light is reflected from a mirror. Still more is reflected from the tops of clouds. As much as 30 percent of the incoming radiation is reflected in this manner. A portion of the radiation is absorbed by checmical compounds in the atmosphere. The ozone layer absorbs much of the ultraviolet radiation, and carbon dioxide, oxygen, and water vapor also absorb radiation. Some of the radiation is scattered by dust and clouds. The various processes serving to reduce the solar energy reaching the earth are illustrated in Figure 4-1.

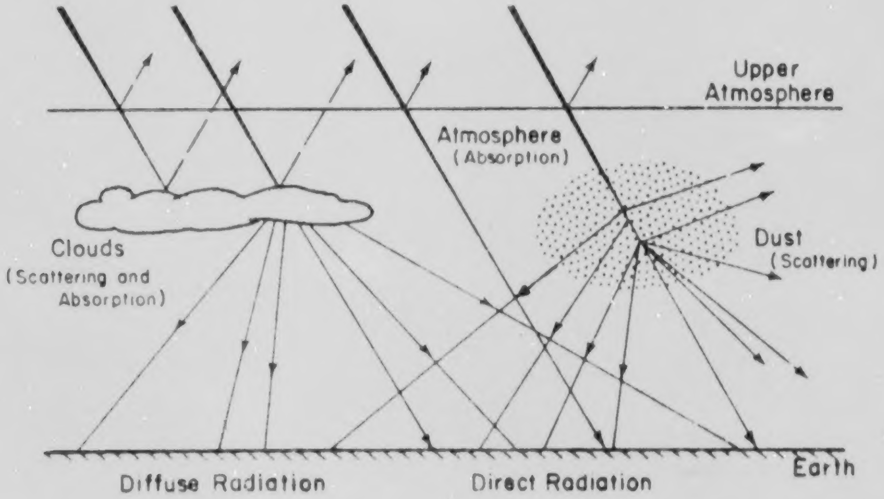
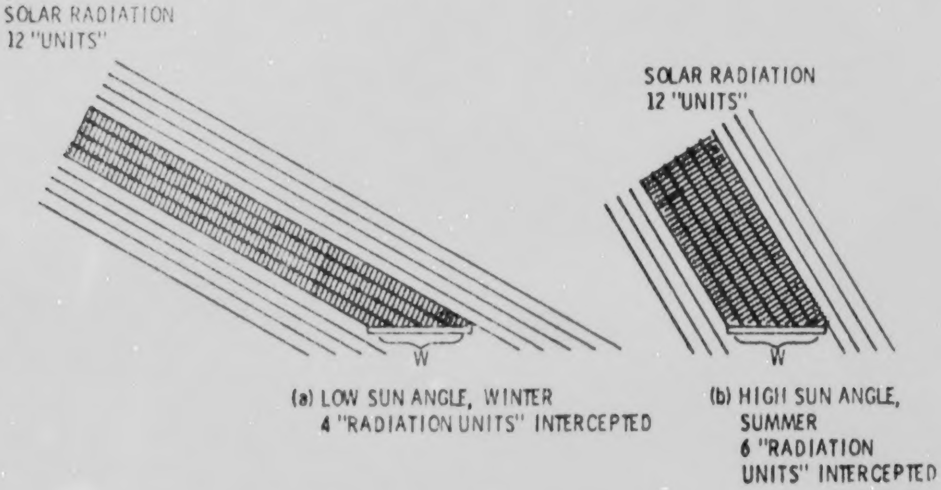

Upper Atmosphere
Atmosphere (Absorption)
Clouds (Scattering and Absorption)
Dust (Scattering)
Earth
Diffuse Radiation
Direct Radiation

Figure 4-1. Atmospheric Effects on Solar Radiation Reaching Earth

Radiation is classified as "direct radiation" if it has not been scattered on passing through the atmosphere, and "diffuse radiation" if it has been scattered. On a "clear" day most of the energy reaches earth as direct radiation, but on a cloudy overcast day, a large portion or all of it may be diffuse.

Monthly Variations

Solar energy on a horizontal surface at any location on earth, if averaged over a month, shows a month-to-month variation. This is due both to seasonal changes in weather, which affect the cloud cover, and the changing angular relationship between the sun and the surface. In the winter the sun is lower in the sky than in the summer, and the resultant larger angle between the sun and a horizontal surface reduces the amount of radiation intercepted by the surface, as shown in Figure 4-2. Figure 4-2-a shows the energy intercepted by a unit width horizontal surface when the sun is at a low angle. In Figure 4-2-b, the sun is shown at a higher angle and a larger amount of energy is intercepted.



(a) LOW SUN ANGLE, WINTER
4 "RADIATION UNITS" INTERCEPTED

(b) HIGH SUN ANGLE, SUMMER
6 "RADIATION UNITS" INTERCEPTED

Figure 4-2. Energy Intercepted by a Unit-Width Horizontal Surface

The monthly variation in solar radiation incident on a horizontal surface is shown in Figure 4-3 for Boulder, Colorado, in Btu/ft^2·day.

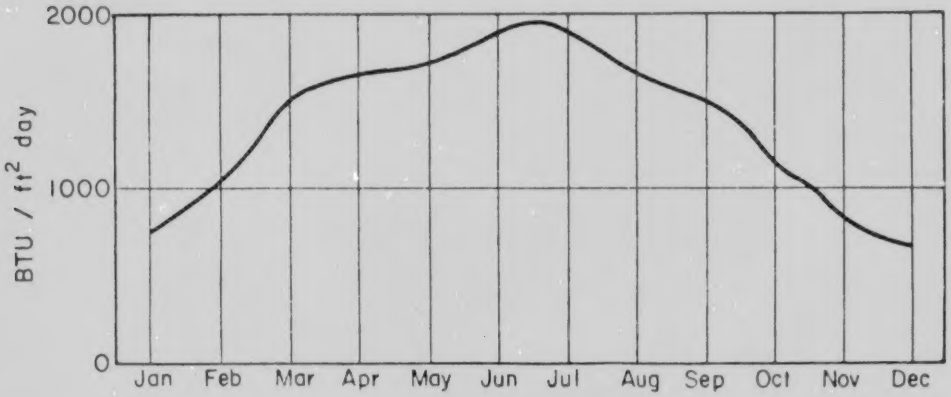


Figure 4-3. Monthly Variation of Average Daily Radiation on a Horizontal Surface, Boulder, Colorado (From the Climatic Atlas of the United States)

The monthly variations in energy on a horizontal surface are shown in Table 4-3 for selected cities in the United States.

Table 4-3

Monthly Variations in Energy on a Horizontal Surface
Selected Cities, (U.S.) (Btu/ft^2·day)

City	December	March	June	September
Chicago, Illinois	280	835	1685	1152
Tucson, Arizona	1122	1987	2572	2098
Washington, D.C.	611	1266	1818	1380
Miami, Florida	1163	1800	1958	1619
Fairbanks, Alaska	22	784	1855	662
Los Angeles, California	887	1730	2193	1851

Daily Variations

The radiation reaching a horizontal surface varies from day to day, mostly due to atmospheric phenomena. Clouds, dust, and pollution can result in changes in the radiation received. Daily variations affect the performance of a solar system but the system can be designed on the basis of average conditions. For a heating system design, the average daily value for the coldest month (usually January) is of particular interest.

Hourly Variations

Hourly variations in available solar energy at a given location are due to the earth's rotation. Early morning sun is at a very low angle and the solar rays must pass through a large thickness of atmosphere. The intensity of the energy received is therefore low. The hourly peak in radiation occurs at noon, when the sun is at the highest angle and is passing through the minimum thickness of the atmosphere. Since winter days are shorter than summer days, the period during which solar energy can be collected varies with season.

The solar intensity on a horizontal surface, measured in Fort Collins, Colorado is shown in Figure 4-4. The smooth curves indicate that these data were obtained on clear days. The presence of clouds would result in breaks in the curves. Note the higher intensity and longer period of measurable radiation during a summer month as opposed to a winter month.

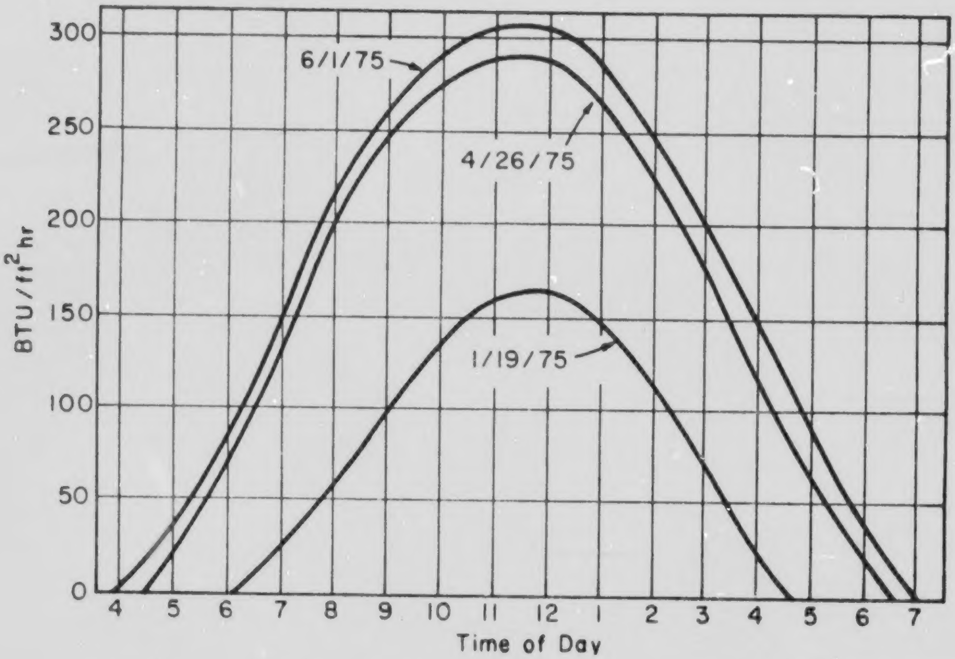
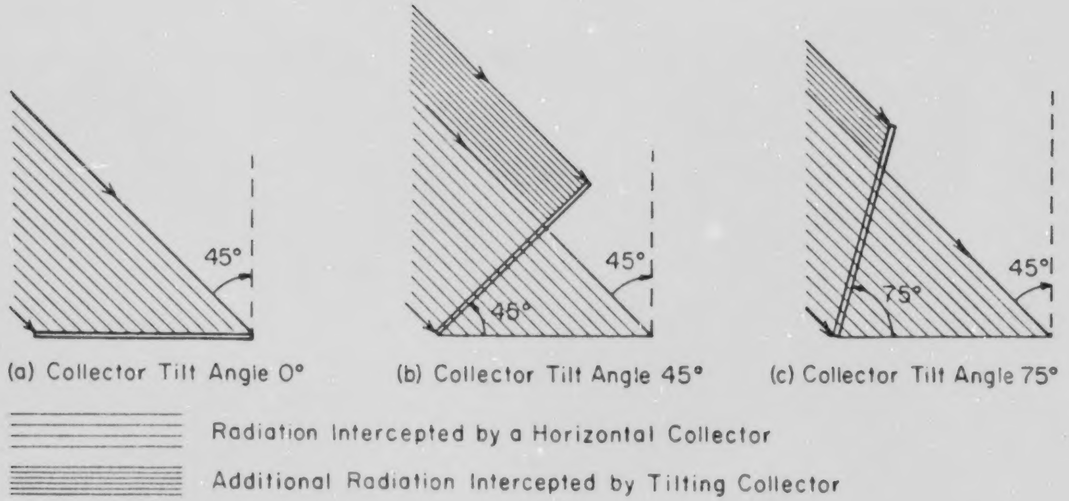


Figure 4-4. Hourly Record of Clear Day Radiation on a Horizontal Surface at Fort Collins, Colorado (Data from Solar House I)

COLLECTOR TILT

Discussion so far has concerned only the radiation on a horizontal surface. In fact, when designing a solar collector, it is advantageous to tilt the collector so that it is perpendicular to the sun's rays. Figure 4-5 illustrates the increase in energy intercepted when a collector is tilted from the horizontal. Note that the optimum tilt angle places the collector at the same angle as the incoming radiation, Figure 4-5(b). When the collector is tilted to an angle greater or smaller than the angle of the incoming radiation the additional energy intercepted is reduced, Figure 4-5(c).

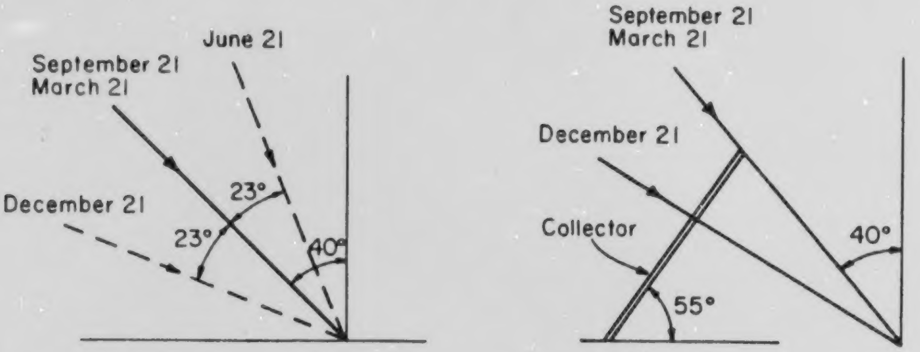
The maximum energy would be intercepted if the collector were to track the sun across the sky. This would mean both following the sun as it moved from east to west during the day and changing the collector tilt to match the season. Tracking collectors are available, but are not as yet practical for use in residential solar heating systems.


45°
45°
45°
45°
75°
Radiation Intercepted by a Horizontal Collector
Additional Radiation Intercepted by Tilting Collector

(a) Collector Tilt Angle 0° (b) Collector Tilt Angle 45° (c) Collector Tilt Angle 75°

Figure 4-5. Effect of Tilting the Collector on Energy Intercepted

A compromise is to tilt the collector so that it is roughly perpendicular to the sun's rays at the time that maximum collection is desired. The best angle for a given location depends on the time of year, since the sun moves across the sky at a lower angle in the winter than in the summer. For heating purposes, maximum collection is desired during the coldest part of the heating season. During this season, from about October until March, the sun's angle varies from 5 degrees to 23 degrees below a line drawn at an angle from the perpendicular equal to the latitude of the location (Figure 4-6-a). To maximize collection during the heating season a good compromise is to tilt the collector at an angle of about latitude plus 15 degrees. In Fort Collins, latitude 40 degrees, the collector should be tilted at about 55 degrees for maximum collection during the heating season. This is illustrated in Figure 4-6-b.



(a) December 21, Sun 23° below Lat. Angle from Perpendicular
June 21, Sun 23° above Lat. Angle from Perpendicular
September 21 and March 21, Sun at Lat. Angle from Perpendicular

(b) Collector Tilted at Latitude +15° Maximizes Winter Collection.

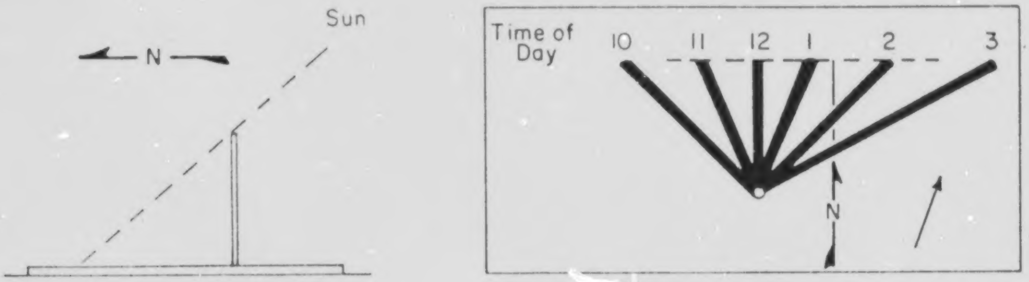
Figure 4-6. (a) Variation of the Angle of Incoming Radiation with Season
(b) Collector Tilt to Maximize Winter Collection in Fort Collins, Colorado (Latitude 40°N)

In the northern hemisphere the collector should be tilted to the south; the opposite is true in the southern hemisphere. To maximize summer collection the collector can be tilted to latitude minus 15 degrees. If both summer and winter collection are desired, a good compromise is to tilt the collector to an angle equal to the latitude.

COLLECTOR ORIENTATION

Since the maximum intensity of direct radiation occurs at noon when the sun is due south (northern hemisphere), the direction of tilt for a collector should be directly south. If this is impossible due to building considerations, a variation of 15 degrees east or west of due south can be tolerated without serious effect on the total energy collected.

An orientation 15 degrees east of south will advance the time of peak collection one hour; an orientation 15 degrees west of south will delay the peak one hour. In some cases a designer can take advantage of the change in peak collection. If, for example, the collection location is partially shaded in the later afternoon, facing the collectors east of south would increase the morning collection.



(a) Equipment Set-up

(b) Resultant Sun-track Diagram Magnetic North Shown

Figure 4-7. Shadow Diagram on a Horizontal Surface Showing the Passage of the Sun Across the Sky and the Determination of Due South, March 23, 1976, Fort Collins, Colorado

DETERMINATION OF DUE SOUTH

The effect of the passage of the sun across the sky during the day is shown in Figure 4-7. Such a shadow diagram can be used to determine due south for collector orientation. A line joining the tips of the shadows lies due east-west. By drawing a perpendicular to this line the north-south line is determined. Note the deviation of true north from magnetic north as determined with a compass.

SOLAR DATA FOR SYSTEM DESIGN

Solar heating and cooling systems can be sized on the basis of monthly average daily radiation on a horizontal surface. Tabular values are listed for each month in Table 4-4, for many cities in the United States. The yearly average daily radiation for the cities is also included in the table. Because the data for specific locations are limited, and estimates for adjacent areas are necessary, it is convenient to arrange a graphical presentation of the distributions of the monthly average daily radiation iso-intensity lines on a map of the United States, as shown in Figures 4-8 through 4-19. The values given in Table 4-4 and Figures 4-8 through 4-19 are in Langleys. For later use in this course, the map of Figure 4-8 has been redrawn, for continental U.S., with units of Btu per square foot in Figure 4-20.

STATE AND STATIONS	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Ann'l
ALASKA, Annette	63	115	236	364	437	438	438	341	258	122	59	41	243
Barrow	*	38	180	380	513	528	429	255	115	41	*	*	206
Bethel	38	138	292	444	457	454	376	252	202	115	44	22	233
Fairbanks	16	71	213	376	461	504	434	317	180	82	26	6	224
Matanuska	32	92	242	356	436	462	409	314	198	100	38	15	224
ARIZONA, Page	[illegible]	382	526	618	695	707	680	596	516	402	310	243	498
Phoenix	301	409	526	638	724	739	658	613	566	449	344	281	520
Tucson	315	391	540	655	729	699	626	588	570	442	356	305	518
ARKANSAS, Little Rock	188	260	353	446	523	559	556	518	439	343	244	187	385
CALIFORNIA, Davis	174	257	390	528	625	694	682	612	493	347	222	148	431
Fresno	184	289	427	552	647	702	682	621	510	376	250	161	450
Inyokern (China Lake)	306	412	562	683	772	819	772	729	635	467	363	300	568
LaJolla	244	302	397	457	506	487	497	464	389	320	277	221	380
Los Angeles WBAS	248	331	470	515	572	596	641	581	503	373	289	241	463
Los Angeles WBO	243	327	436	483	555	584	651	581	500	362	281	234	436
Riverside	275	367	478	541	623	680	673	618	535	407	319	270	483
Santa Maria	263	346	482	552	635	694	680	613	524	419	313	262	481
Soda Springs	222	316	374	551	615	691	760	681	510	357	248	182	459
COLORADO, Boulder	201	268	401	460	460	525	520	439	412	310	222	182	367
Grand Junction	227	324	434	546	615	708	676	595	514	373	260	212	456
Grand Lake (Granby)	212	313	423	512	552	632	600	505	476	361	234	184	417
D.C., Washington (C.O.)	174	266	344	411	551	494	536	446	375	299	211	166	356
American University	158	231	322	398	467	510	496	440	364	278	192	141	333
Silver Hill	177	247	342	438	513	555	511	457	391	293	202	156	357
FLORIDA, Apalachicola	298	367	441	535	603	578	529	511	456	413	332	262	444
Belle Isle	297	333	412	463	483	464	488	461	400	366	313	291	397
Gainesville	267	343	427	517	579	521	488	483	418	347	300	233	410
Miami Airport	349	415	389	540	553	532	532	505	440	384	353	316	451
Tallahassee	274	311	423	499	547	521	508	542	*	*	292	230	---
Tampa	327	391	474	539	596	574	534	494	452	400	356	300	453
GEORGIA, Atlanta	218	290	380	488	533	562	532	508	416	344	268	211	396
Griffin	234	295	385	522	570	577	556	522	435	368	283	201	413
HAWAII, Honolulu	363	422	516	559	617	615	615	612	573	507	426	371	516
Mauna Loa Obs.	522	576	680	689	727	*	703	642	602	560	504	481	---
Pearl Harbor	359	420	487	529	573	566	598	567	539	466	386	343	484
IDAHO, Boise	138	236	343	485	585	636	670	576	460	301	182	124	395
Twin Falls	163	240	355	462	552	592	602	540	432	286	176	131	378
ILLINOIS, Chicago	96	147	227	331	424	458	473	403	313	207	120	76	273
Lemont	170	242	340	402	506	553	540	498	398	275	165	138	352
INDIANA, Indianapolis	144	213	316	396	488	543	541	490	405	293	177	132	345
IOWA, Ames	[illegible]	[illegible]	326	403	480	541	436	460	367	274	187	143	345
KANSAS, Dodge City	255	316	418	528	568	650	642	592	493	380	285	234	447
Manhattan	192	264	345	433	527	551	531	526	410	292	227	156	371
KENTUCKY, Lexington	172	263	357	480	581	628	617	563	494	357	245	174	411
LOUISIANA, Lake Charles	245	306	397	481	555	591	526	511	449	402	300	250	418
New Orleans	[illegible]	297	375	412	449	443	417	416	383	357	278	198	347
Shreveport	232	292	384	446	558	557	578	528	414	354	254	205	400
MAINE, Caribou	133	231	364	400	476	470	508	448	336	212	111	107	316
Portland	152	235	352	409	514	539	561	488	383	278	157	137	350
MASSACHUSETTS, Amherst	116	*	300	*	431	514	*	---	---	---	152	124	---
Blue Hill	153	221	319	389	469	510	502	449	354	266	162	135	328
Boston	129	194	290	350	445	483	486	411	334	235	136	115	301
Cambridge	153	225	323	400	420	476	482	464	367	253	164	124	322
East Wareham	140	218	305	385	452	508	495	436	365	258	163	140	322
Lynn	118	209	300	394	454	549	528	432	341	241	135	107	317
MICHIGAN, East Lansing	[illegible]	200	297	357	483	547	540	466	373	255	136	108	311
Sault Ste. Marie	130	225	356	416	523	557	573	472	322	216	105	96	333
MINNESOTA, St. Cloud	168	260	366	426	496	535	557	486	366	237	146	124	348
MISSOURI, Columbia (C.O.)	173	251	340	434	530	574	574	522	453	322	225	158	380
University of Missouri	169	248	324	429	501	560	583	509	417	324	177	146	365

STATE AND STATIONS	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Ann'l
MONTANA, Glasgow	154	258	385	466	568	605	645	531	410	267	154	116	368
Great Falls	140	232	366	434	528	583	639	532	407	264	154	112	366
Summit	122	162	268	414	462	493	560	510	354	216	102	76	312
NEBRASKA, Lincoln	188	259	350	416	494	544	568	484	396	296	199	159	363
North Omaha	193	299	365	463	516	546	568	519	410	298	204	170	379
NEVADA, Ely	236	339	468	563	625	712	647	618	518	394	289	218	469
Las Vegas	277	384	519	621	702	748	675	627	551	429	318	258	509
NEW JERSEY, Seabrook	157	227	318	403	482	527	509	455	385	278	192	140	339
NEW HAMPSHIRE, Mt. Washington	117	218	238	*	*	*	---	---	*	*	*	96	---
NEW MEXICO, Albuquerque	303	386	511	618	686	726	683	626	554	438	334	276	512
NEW YORK, Ithaca	116	194	272	334	440	501	515	453	346	231	120	96	302
New York Central Park	130	199	290	369	432	470	459	389	331	242	147	115	298
Sayville	160	249	335	415	494	565	543	462	385	289	186	142	352
Schenectady	130	200	273	338	413	448	441	397	299	218	128	104	282
Upton	155	232	339	428	502	573	543	475	391	293	182	146	355
NORTH CAROLINA, Greensboro	200	276	354	469	531	564	544	485	406	322	243	197	383
Hatteras	238	317	426	569	635	652	625	562	471	358	282	214	443
Raleigh	235	302	*	466	494	564	535	476	379	307	235	199	---
NORTH DAKOTA, Bismarck	157	250	356	447	550	590	617	516	390	272	161	124	369
OHIO, Cleveland	125	183	303	286	502	562	562	494	278	289	141	115	335
Columbus	128	200	297	391	471	562	542	477	422	286	176	129	340
Put-in-Bay	126	204	302	386	468	544	561	487	382	275	144	109	332
OKLAHOMA, Oklahoma City	251	319	409	494	536	615	610	593	487	377	291	240	436
Stillwater	205	289	390	454	504	600	596	545	455	354	269	209	405
OREGON, Astoria	90	162	270	375	492	469	539	461	354	209	111	79	301
Corvallis	89	*	287	406	517	570	676	558	397	235	144	80	---
Medford	116	215	336	482	592	652	698	605	447	279	149	93	389
PENNSYLVANIA, Pittsburgh	94	169	216	317	429	491	497	409	339	207	118	77	280
State College	133	201	295	380	456	518	511	444	358	256	149	118	318
RHODE ISLAND, Newport	155	232	334	405	477	527	[illegible]	455	377	271	176	139	338
SOUTH CAROLINA, Charleston	252	314	388	512	551	564	520	501	404	338	286	225	404
SOUTH DAKOTA, Rapid City	183	277	400	482	532	585	590	541	435	315	204	158	392
TENNESSEE, Nashville	149	228	322	432	503	551	530	473	403	308	208	150	355
Oak Ridge	161	239	331	450	518	551	526	478	416	318	213	163	364
TEXAS, Brownsville	297	341	402	456	564	610	627	568	475	411	296	263	442
El Paso	333	430	547	654	714	729	666	640	576	460	372	313	536
Fort Worth	250	320	427	488	562	651	613	593	503	403	306	245	445
Midland	283	358	476	550	611	617	608	574	522	396	325	275	466
San Antonio	279	347	417	445	541	612	639	585	493	398	295	256	442
UTAH, Flaming Gorge	238	298	443	522	565	650	599	538	425	352	262	215	426
Salt Lake City	163	256	354	479	575	621	620	551	446	316	204	146	394
VIRGINIA, Mt. Weather	172	274	338	414	508	525	510	430	375	281	202	168	350
WASHINGTON, North Head	*	167	257	432	509	487	486	436	321	205	122	77	---
Friday Harbor	87	157	274	418	514	578	586	507	351	194	102	75	320
Prosser	117	222	351	521	616	680	707	604	458	274	136	100	399
Pullman	121	205	304	462	558	653	699	562	410	245	146	96	372
University of Washington	67	126	245	364	445	461	496	435	299	170	93	59	272
Seattle-Tacoma	75	139	265	403	503	511	566	452	324	188	104	64	300
Spokane	119	204	321	474	563	596	665	556	404	225	131	75	361
WISCONSIN, Madison	148	220	313	394	466	514	534	452	348	241	145	115	324
WYOMING, Lander	226	324	452	548	587	678	651	586	472	354	239	196	443
Laramie	216	290	424	608	554	643	606	636	438	324	229	186	408
INLAND STATIONS													
Canton Island	588	626	634	604	561	540	550	597	640	651	600	579	597
San Juan, P.R.	404	481	580	622	519	536	639	540	531	460	411	411	512
Swan Island	442	496	615	646	625	544	588	591	535	457	304	382	526
Wake Island	438	518	577	627	642	656	629	623	587	525	482	421	560

NOTES:
- * Denotes only one year of data for the month -- no means computed
- --- No data for the month (or incomplete data for the year)
- # Barrow is in darkness during the winter months
- - Madison data fter 1957 not used due to exposure influence
- ‡ Riverside data prior to March 1952 not used - instrumental discrepancies

Langley is the unit used to denote one gram calorie per square centimeter.

Table 4-4. Mean Daily Solar Radiation (Langleys)

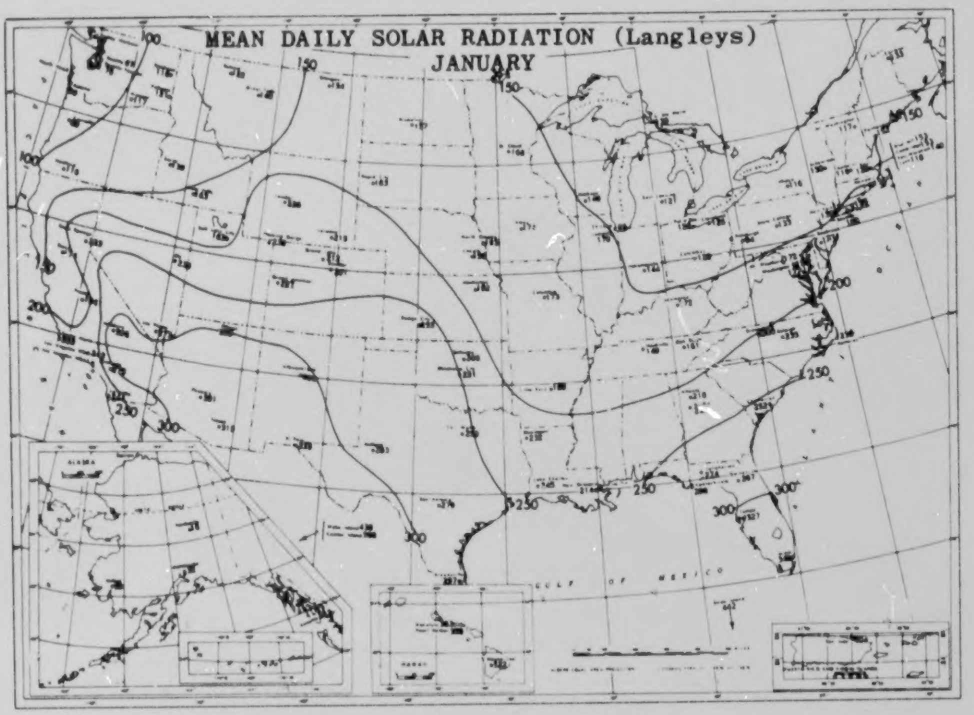

MEAN DAILY SOLAR RADIATION (Langleys)
JANUARY
100
150
200
250
300
GULF OF MEXICO

Figure 4-8. Mean Daily Solar Radiation (Langleys), January

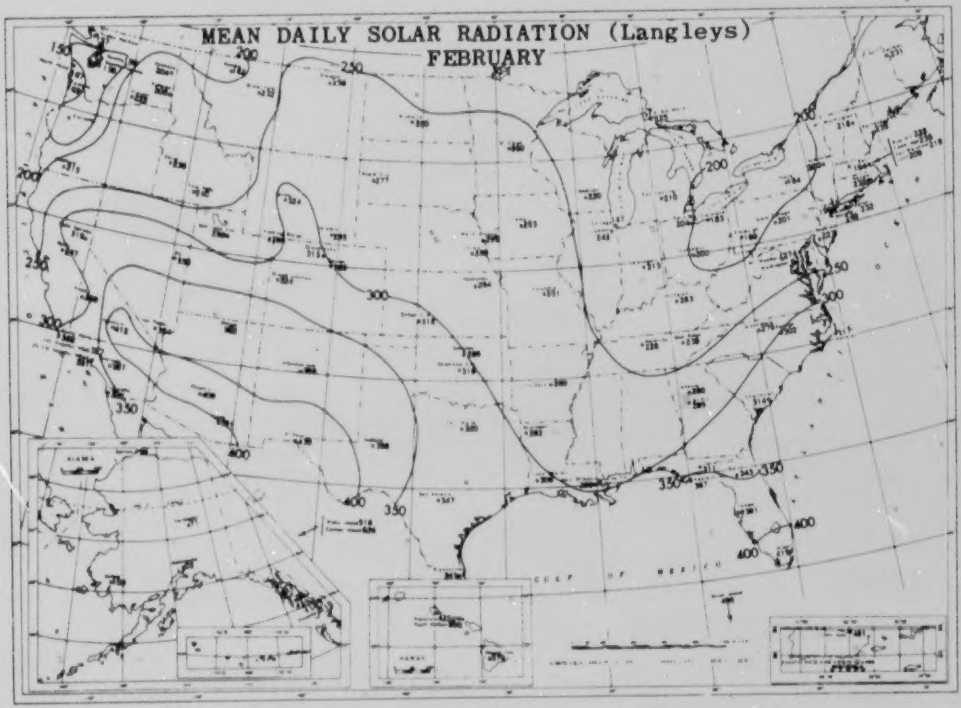

MEAN DAILY SOLAR RADIATION (Langleys)
FEBRUARY
150
200
250
300
350
400
GULF OF MEXICO

Figure 4-9. Mean Daily Solar Radiation (Langleys), February

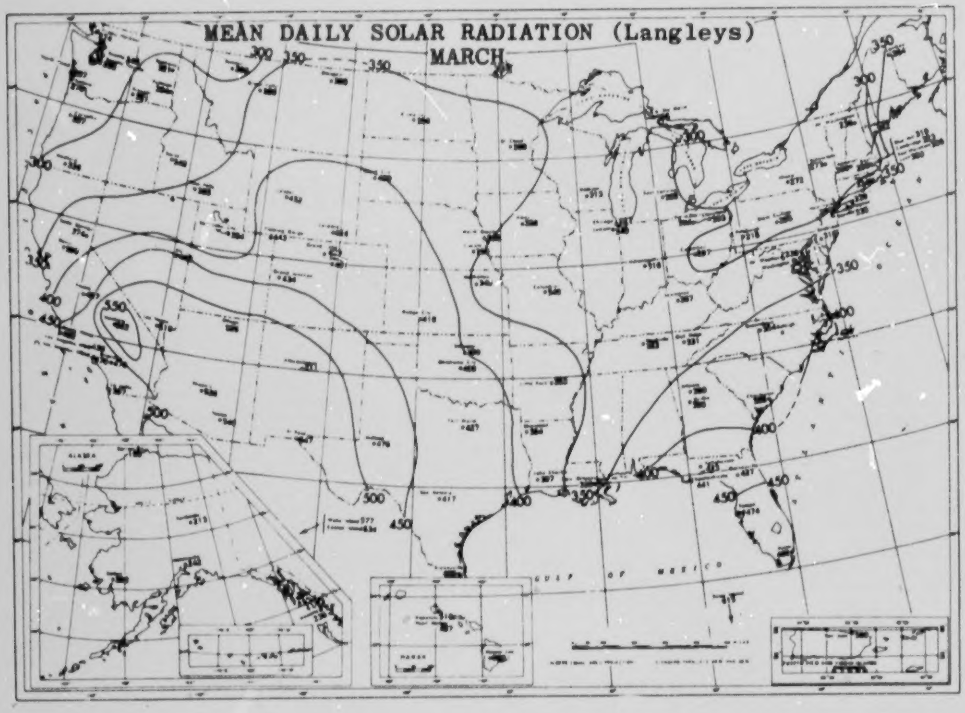

MEAN DAILY SOLAR RADIATION (Langleys)
MARCH
300
350
350
350
300
300
350
350
350
400
450
550
500
500
450
400
350
400
400
450
450
450
GULF OF MEXICO
ALASKA
HAWAII

Figure 4-10. Mean Daily Solar Radiation (Langleys), March

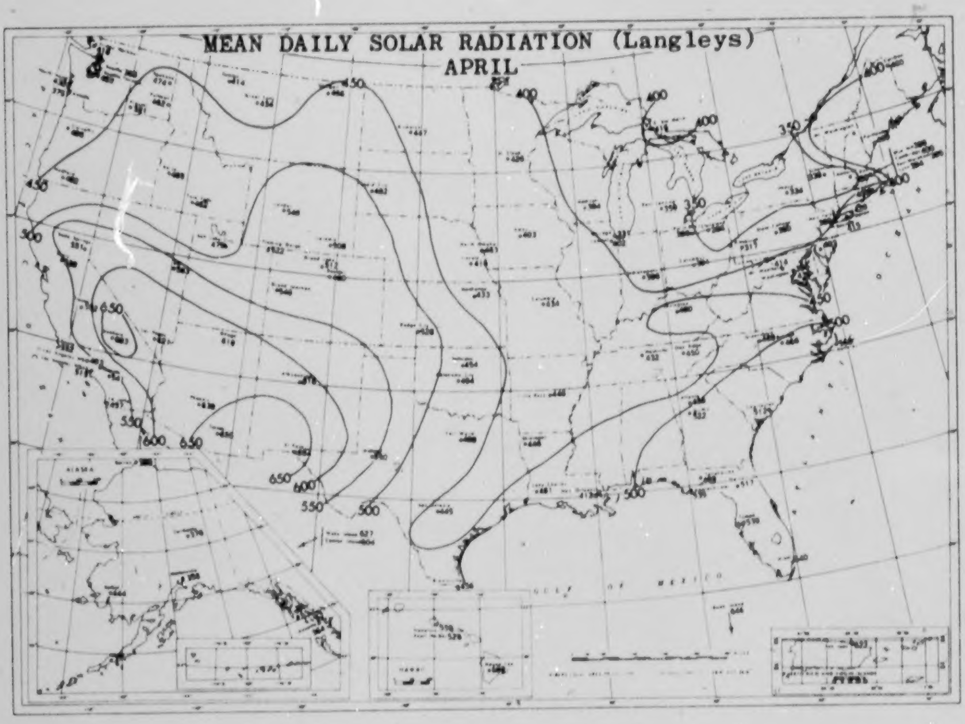

MEAN DAILY SOLAR RADIATION (Langleys)
APRIL
450
400
400
400
400
350
400
450
500
650
550
600
650
650
600
550
500
350
450
400
500
GULF OF MEXICO
ALASKA
HAWAII

Figure 4-11. Mean Daily Solar Radiation (Langleys), April

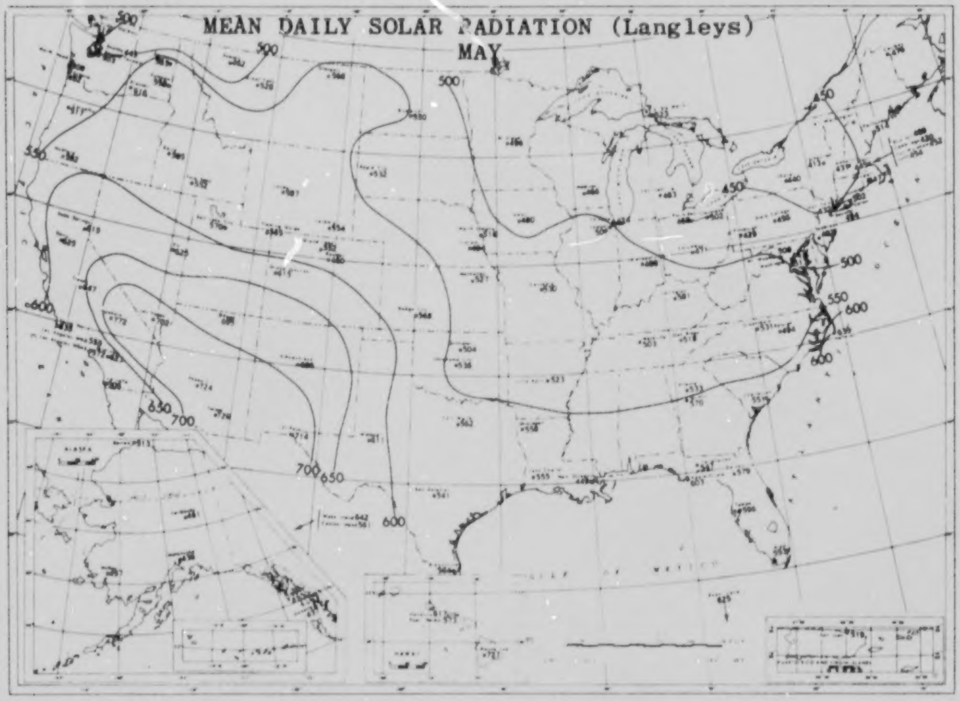

MEAN DAILY SOLAR RADIATION (Langleys)
MAY
500
450
550
600
650
700

Figure 4-12. Mean Daily Solar Radiation (Langleys), May

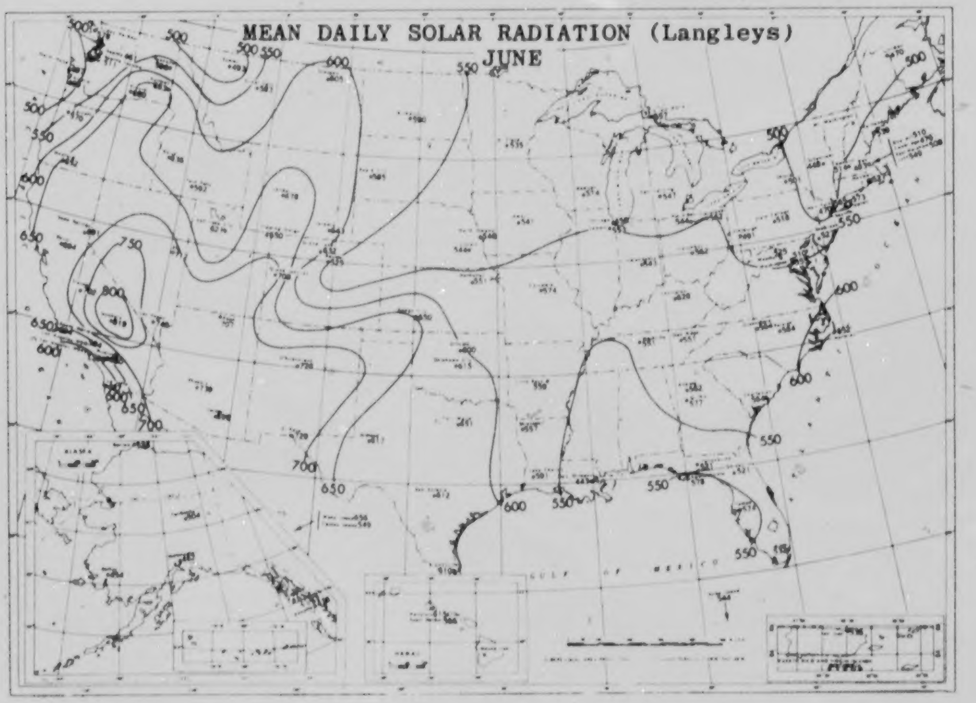

MEAN DAILY SOLAR RADIATION (Langleys)
JUNE
500
550
600
650
700
750
800

Figure 4-13. Mean Daily Solar Radiation (Langleys), June

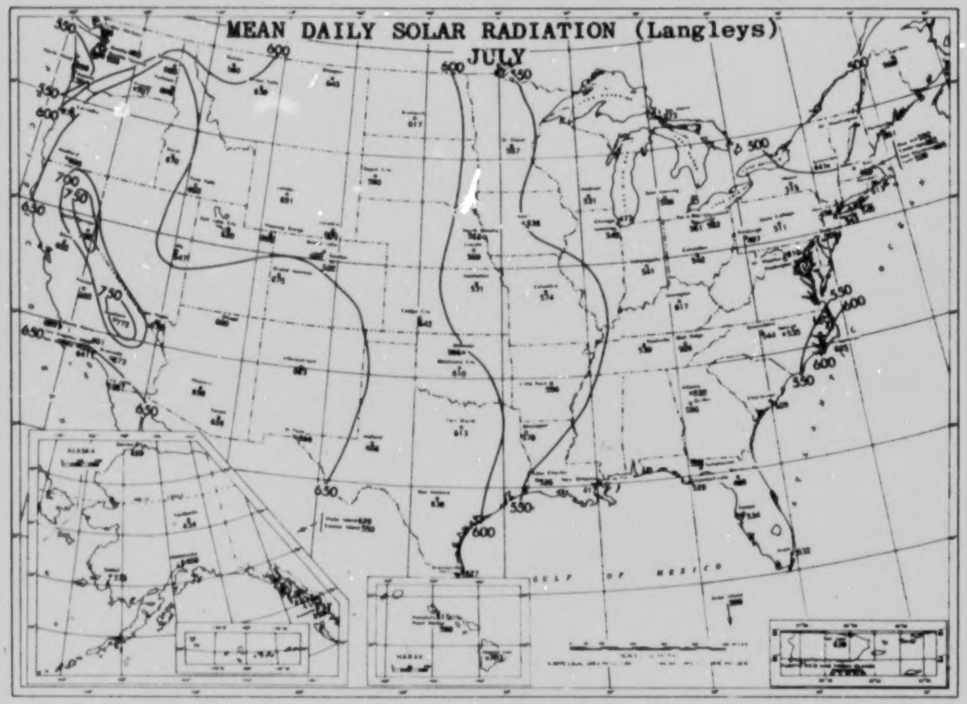

MEAN DAILY SOLAR RADIATION (Langleys)
JULY
350
550
600
650
700
750
500
550
600
650
550
600

Figure 4-14. Mean Daily Solar Radiation (Langleys), July

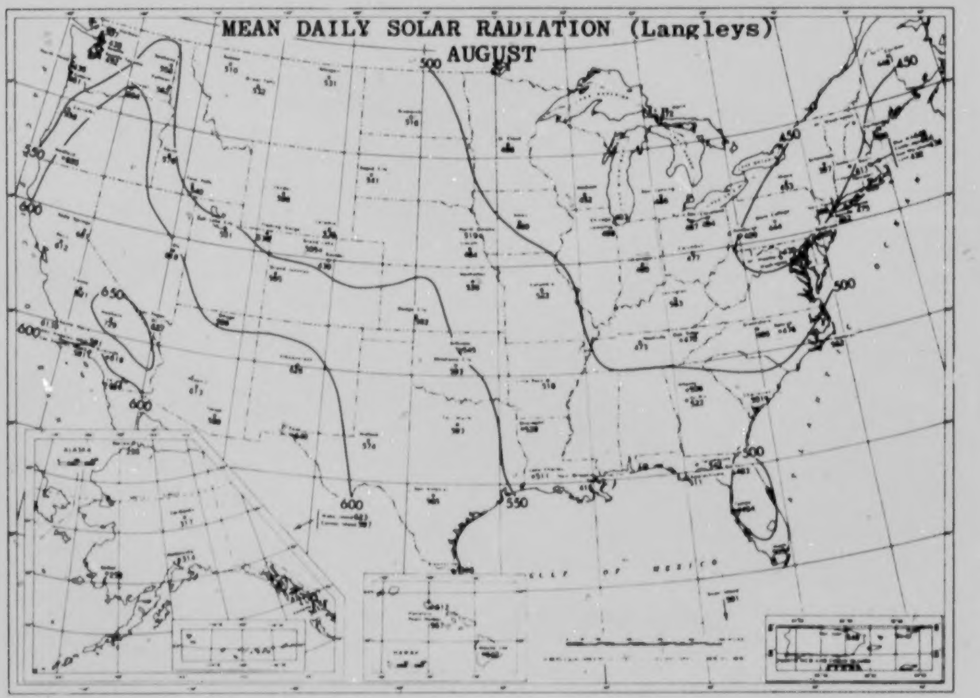

MEAN DAILY SOLAR RADIATION (Langleys)
AUGUST
500
450
550
600
650
500
600
550
500

Figure 4-15. Mean Daily Solar Radiation (Langleys), August

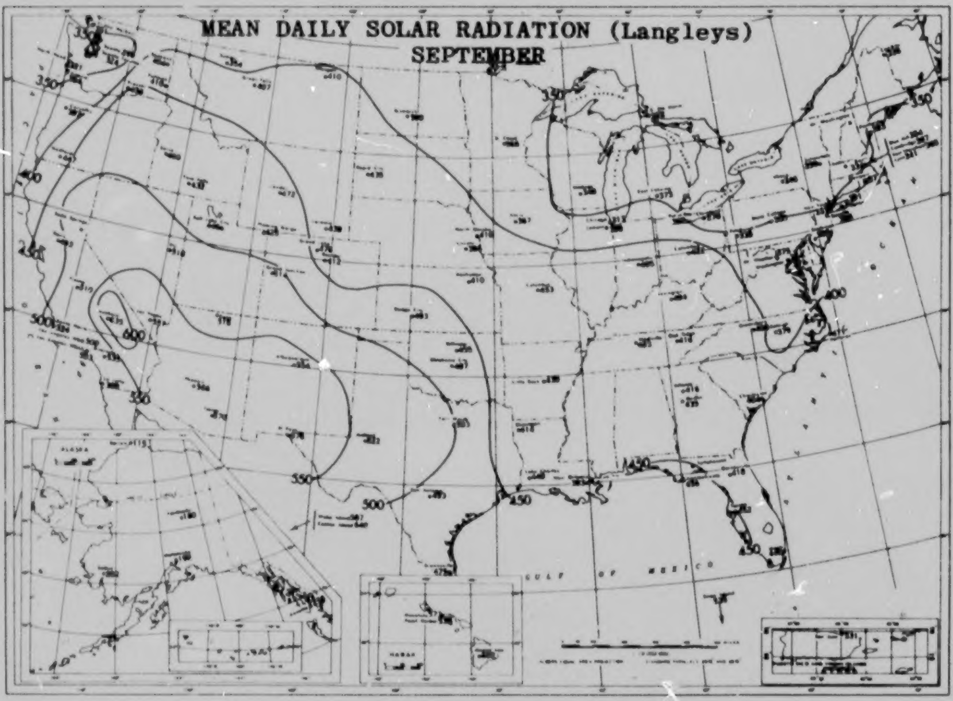

MEAN DAILY SOLAR RADIATION (Langleys)
SEPTEMBER
350
350
400
450
500
600
550
550
500
450
350
400
450
450
GULF OF MEXICO

Figure 4-16. Mean Daily Solar Radiation (Langleys), September

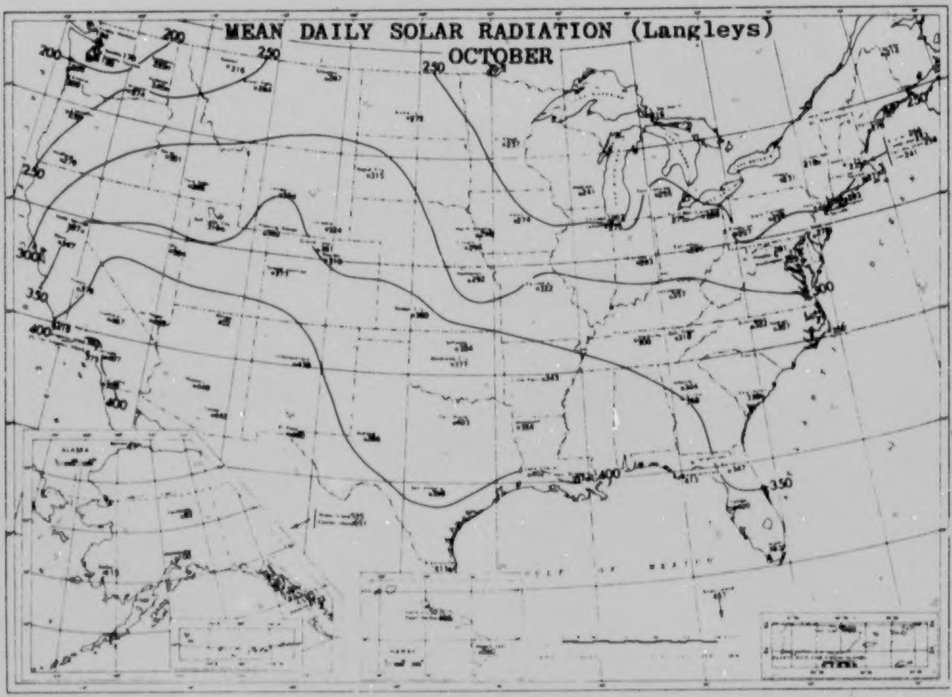

MEAN DAILY SOLAR RADIATION (Langleys)
OCTOBER
200
200
250
250
250
300
350
400
400
300
400
350

Figure 4-17. Mean Daily Solar Radiation (Langleys), October

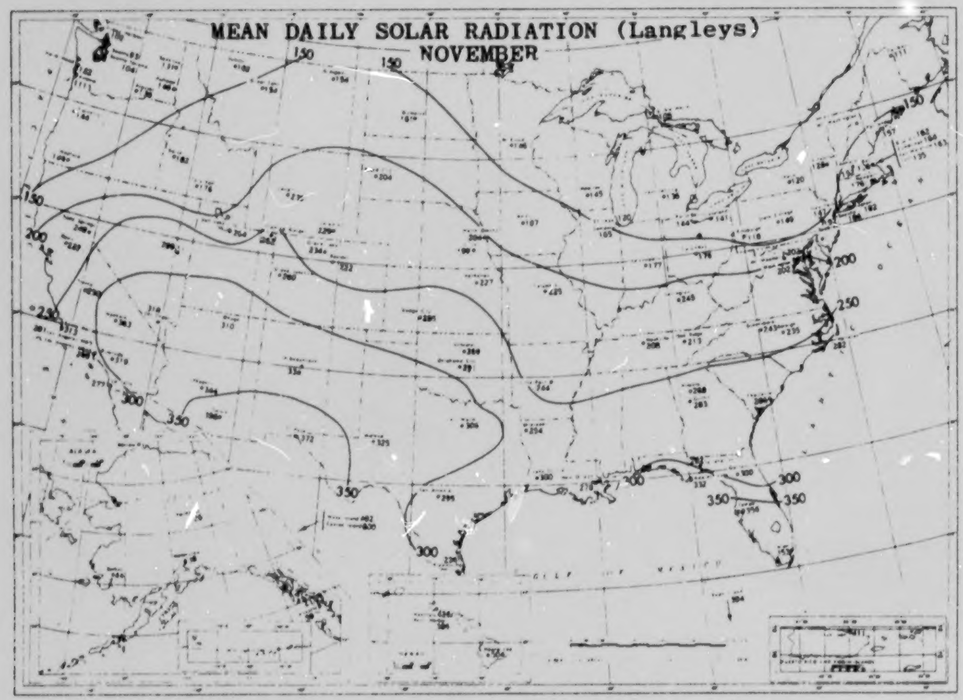

MEAN DAILY SOLAR RADIATION (Langleys)
NOVEMBER
150
150
150
150
200
200
250
250
300
300
300
350
350
350
350

Figure 4-18. Mean Daily Solar Radiation (Langleys), November

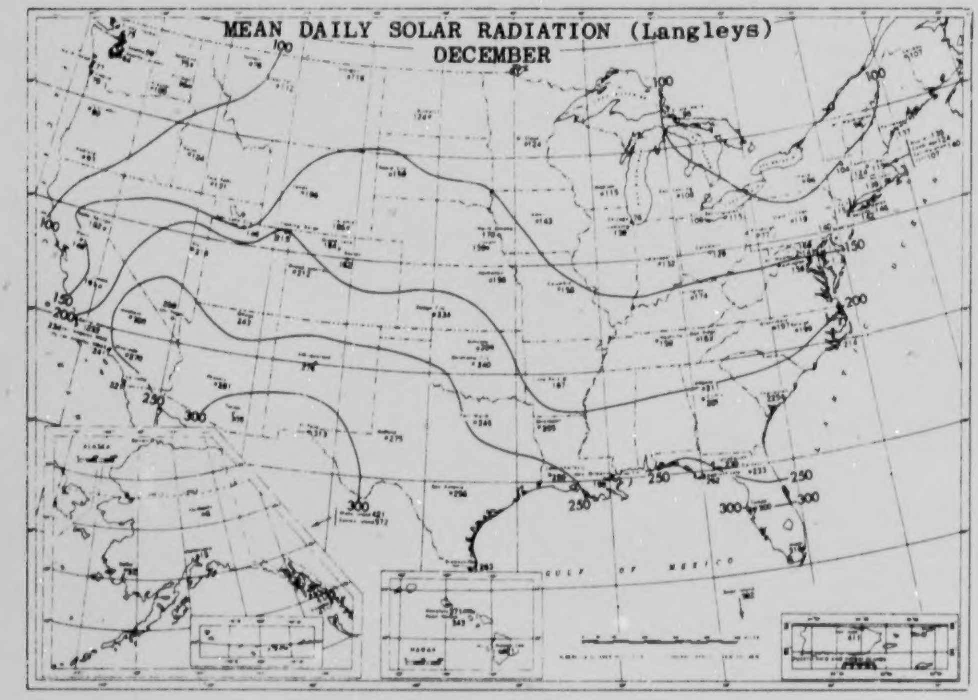

MEAN DAILY SOLAR RADIATION (Langleys)
DECEMBER
100
100
100
100
150
150
200
200
250
250
250
250
300
300
300
300

Figure 4-19. Mean Daily Solar Radiation (Langleys), December

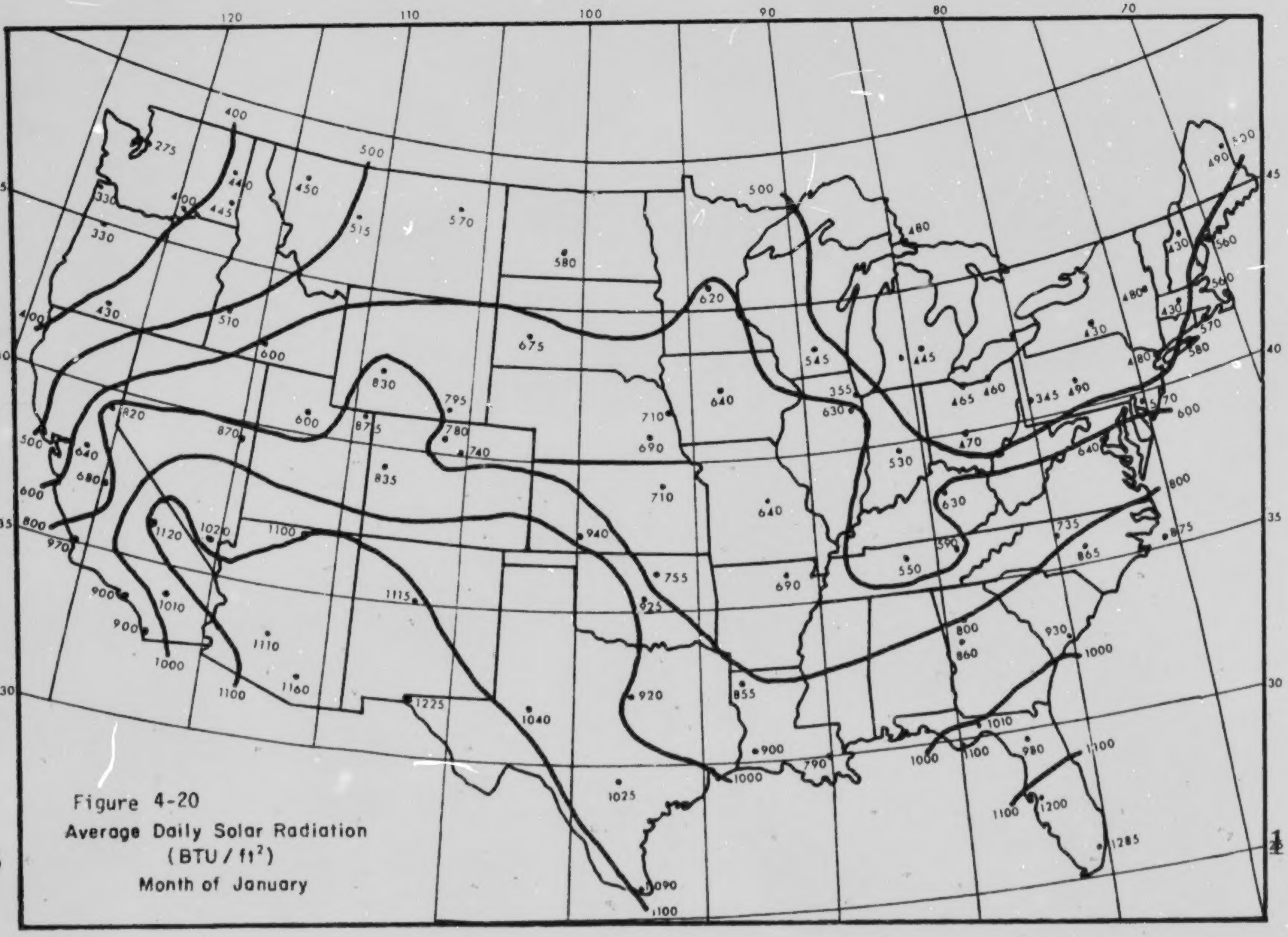

120
110
100
90
80
70
45
40
35
30
275
330
330
400
440
445
400
450
500
515
570
580
400
430
510
600
675
620
500
480
545
445
430
480
430
560
560
570
580
490
530
355
630
640
710
690
830
795
600
875
780
740
820
870
500
640
680
600
835
710
640
530
465
460
345
490
480
570
600
470
640
630
800
550
590
735
865
875
800
970
1120
1020
1100
940
755
625
690
900
1010
900
1000
1115
1110
1100
1160
1225
1040
920
855
800
860
930
1000
1010
1000
1100
980
1100
900
790
1000
1025
1100
1200
1285
1090
1100

Figure 4-20
Average Daily Solar Radiation
(BTU / ft²)
Month of January

TRAINING COURSE IN
THE PRACTICAL ASPECTS OF
SIZING, INSTALLATION, AND OPERATION OF SOLAR HEATING AND COOLING SYSTEMS
FOR
RESIDENTIAL BUILDINGS

MODULE 5

FLUID HEATING SOLAR COLLECTORS

SOLAR ENERGY APPLICATIONS LABORATORY
COLORADO STATE UNIVERSITY
FORT COLLINS, COLORADO

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INTRODUCTION

The purpose of this module is to identify and explain those principles which influence the design, operation, and installation of solar collectors and to indicate items that may require maintenance.

OBJECTIVE

At the end of this module, the trainee should be able to:

1. Identify and describe the functions of the individual components of a solar collector,
2. Compare the performance between various collectors,
3. Describe methods of preventing corrosion and freezing of collectors,
4. Describe the function of various fluids in collectors,
5. Recognize effect of system design changes on collector performance,
6. Install a typical solar collector array,
7. Explain the factors contributing to solar collector durability.

BASIC PRINCIPLES

A solar collector is a means of intercepting incident solar radiation, converting this radiation to heat, and delivering useful energy to the building. A collector consists of an absorber plate (commonly a black metal surface) which absorbs the incident solar radiation and converts this solar energy to heat. A portion of this heat is transferred to a fluid and then transported to another part of the system. In the process of collecting energy and transferring the heat, the absorber plate will lose some of the heat to its surroundings, so other components of the solar collector are provided to reduce the heat losses.

Heat is lost from the absorber plate by radiation, convection, and conduction. Insulation beneath the absorber reduces the heat loss through the back of the collector, and the transparent covers reduce the heat losses from the "front" of the collector. A glass cover, which is opaque to the thermal radiation emitted by the plate, will reduce convection losses to the outside air because the air space between the absorber plate and cover restricts convective air motion.

The useful energy from a solar collector is transferred to a fluid and delivered directly to the building or to storage, where it can be used at a later time. The two principal types of fluid heating solar collectors are liquid-heating solar collectors and air-heating solar collectors. Liquid heating collectors normally use water or a solution of water and ethylene glycol (antifreeze), but numerous other liquids can be used.

Flat-plate solar collectors absorb both direct and diffuse solar radiation. This is an important aspect of collectors, especially in areas where a large proportion of solar radiation is in the form of diffuse or reflected radiation.

SOLAR SWIMMING POOL HEATERS

A solar collector should be designed to provide heat at the required temperature. For example, to heat swimming pools, collectors may deliver heat at a very low temperature and, consequently, require simple and inexpensive designs.

Perhaps the simplest method of heating swimming pools with solar energy is to cover the water surface with a large, thin, transparent (to solar radiation) plastic sheet. The cover will reduce heat loss due to evaporation, as well as heat losses by other forms and can be expected to increase the pool temperature by 12 to 20°F above mean ambient temperature (a summer average of about 15°F).

More conventional flat-plate collectors, available for heating swimming pools, usually consist only of a black plastic absorber. Usually these simple collectors do not utilize any transparent covers at all, since the plastic is not capable of withstanding the high temperatures that would be experienced under no flow conditions. While the fluid temperatures achieved by these collectors are low, they are adequate for swimming pool heating. The efficiency of a simple flat-plate collector is low, but the installed cost of the collector is also low, so that the cost-effectiveness, in terms of Btu per dollar, is reasonably high.

FLAT-PLATE LIQUID-HEATING SOLAR COLLECTORS

The cross-section of a practical flat-plate liquid-heating solar collector with a tube-in-plate absorber is shown in Figure 5-1. The drawing shows a collector mounted on roof sheathing, but the collector could be mounted directly on the roof trusses and a sheathing is not needed if the insulation can be supported.

The spacing between the glass cover and absorber is about one inch, with another inch between the lower cover glass and the top cover glass.

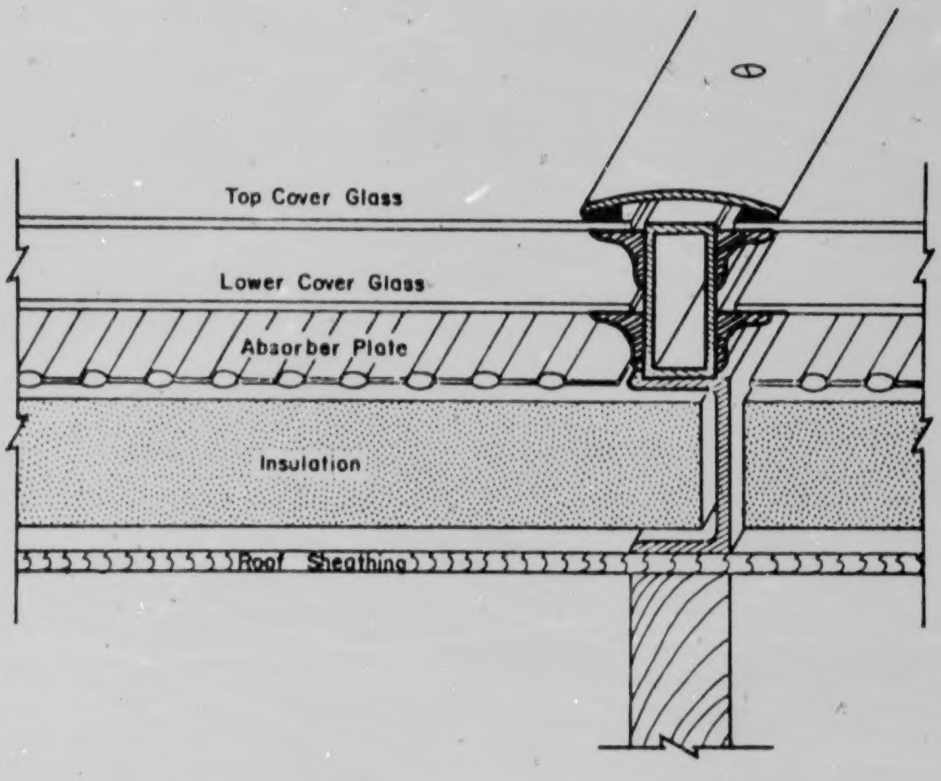

Top Cover Glass
Lower Cover Glass
Absorber Plate
Insulation
Roof Sheathing

Figure 5-1. Solar Collector Cross-Section

Two to four inches of insulation would be appropriate. A composite insulation consisting of one inch of unbonded glass fiber mat on 1.5 inches of Fesco-Foam® insulation would be suitable, with the glass fiber adjacent to the absorber plate to withstand a possible high temperature.

A collector which can be fabricated at the factory is shown in Figure 5-2. The unit is installed as a module in an array of collectors. A factory-assembled collector is typically about 3 feet by 6 feet, although there is considerable variation in sizes. The depth of the collector is about seven inches.

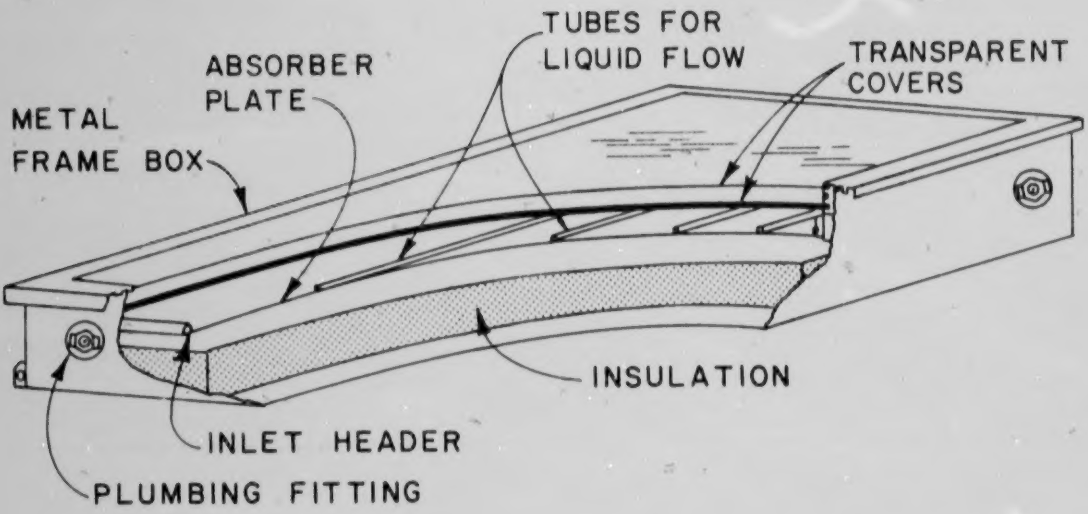

TUBES FOR LIQUID FLOW
TRANSPARENT COVERS
ABSORBER PLATE
METAL FRAME BOX
INSULATION
INLET HEADER
PLUMBING FITTING

Figure 5-2. Solar Collector Module

TRANSPARENT COVERS

The physical and optical stability of thin transparent plastic films and sheets under ultraviolet radiation and also at the high temperatures that are developed in solar collectors is not well established. Tedlar and polycarbonate sheets have been used, but glass is commonly used for solar collectors. The optimum number of glass covers depends on collector design, the fluid temperature desired, and the outdoor air temperature. For flat-plate collectors in systems that are used only for winter heating, one glass cover is suitable where average winter air temperature is greater than about 45°F. Two glass covers should be used for collectors in colder climates.

While there is some questions of glass breakage from wind and hail storms, use of tempered glass and small collector widths will reduce risks of glass breakage.

ABSORBER PLATE

Material

Metal is the best material for absorber plates. In liquid-heating collectors, the tubes must be thermally bonded to the absorber plates to conduct the heat from the plate to the tube wall. The thermal contact between the tube and the absorber plate is satisfactory with tube-in-sheet absorber plates. The cost of an 1100 alloy aluminum Roll Bond ^{R} is about one dollar per square foot.

A major difficulty in the use of aluminum is the possibility of corrosion of the tube walls. While corrosion can be effectively limited by additives in the heat transfer fluid, it is not totally inhibited. Copper or steel absorber plates are also used quite extensively, but copper tubes are expensive and steel plates are heavy. Some absorber plates consist of copper tubes bonded to a less expensive metal plate.

Pressure Drop Through the Absorber Plate

The pressure drop through the tubes of an absorber plate is a function of the flow rate through the tubes. The flow rate, in turn, is selected on the basis of a desired temperature increase in the heat transfer liquid from the inlet to the outlet. The flow rate will vary with the temperature in the fluid because the viscosity of the liquid varies with temperature. A temperature rise across the collector of about 15°F with peak insolation is a reasonable design basis. The flow rate through the tube to achieve the temperature rise is about 0.02 gallons per minute for each square foot of collector.

It is important to achieve a finite pressure drop along the tubes attached to the absorber plate (or in the plate) to assure satisfactory flow distribution among all the tubes. A practically-sized absorber plate is shown in Figure 5-3 for purpose of illustration. In this design, the risers are about 7.5 feet long and the headers are approximately 2.5 feet long. The total head loss across the absorber plate from point A to point B is the same along any riser tube. The head loss is equal to the head loss across one riser plus the head loss in one header.

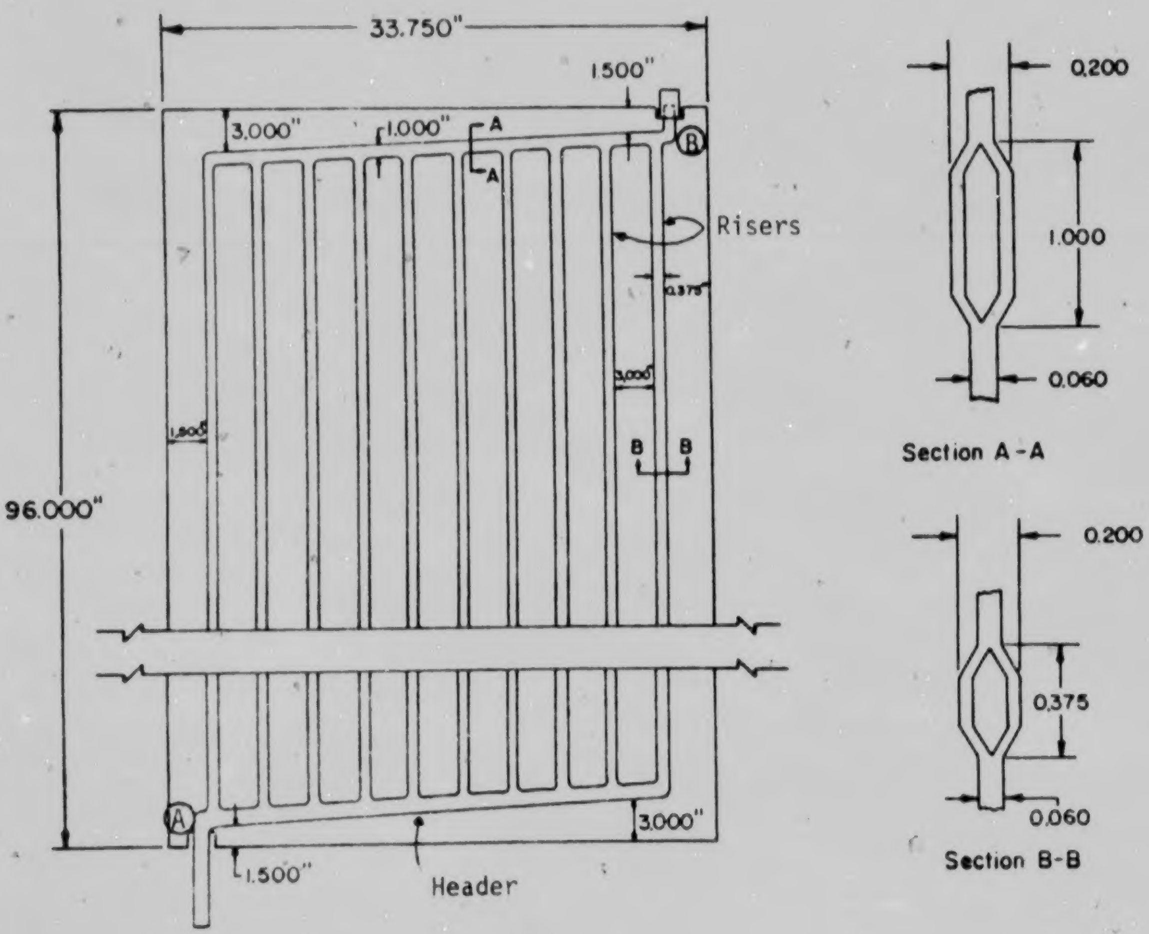

33.750"
1.500"
3.000"
1.000"
A
A
B
Risers
0.375
3.000
1.500
B
B
96.000"
A
3.000"
1.500"
Header
0.200
1.000
0.060
Section A-A
0.200
0.375
0.060
Section B-B

Figure 5-3. CSU Solar Collector Absorber Plate Dimensions

It has been experimentally determined that satisfactory flow distribution in a solar collector is achieved when the head loss along one header is less than one-tenth of the total head loss from A to B. Likewise, when solar collector arrays are arranged, it is important that the flows be equal through all the collectors. The headers, shown in Figure 5-4, should be sized so that the head loss along one header is about one-tenth the total head loss from points A to B.

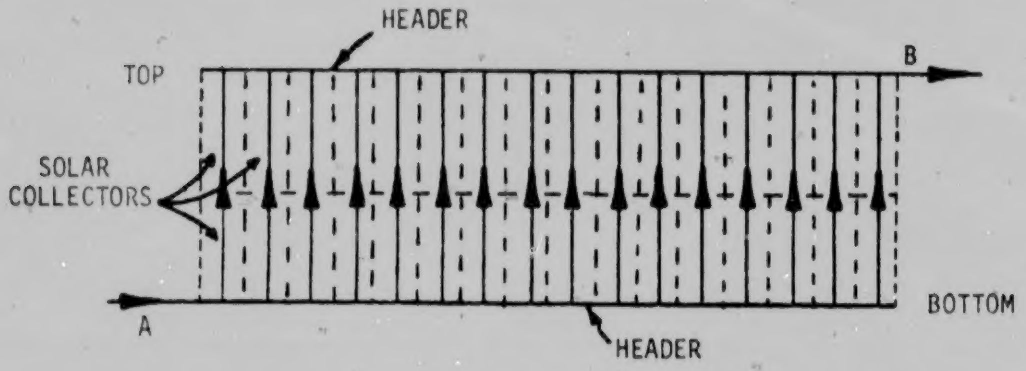


Figure 5-4. Definition Sketch for Fluid Flow Distribution, A Solar Collector Array

BLACK ABSORBER COATING

There are many types of paints to coat absorber surfaces. An acceptable black absorber coating, suitable for air and liquid collectors is a 3M brand Nextel® Black Velvet Coating. A Nextel® primer is recommended before the coating is applied. One gallon of the paint (also the primer) covers about 200 square feet of absorber surface area. The solar reflectance of this coating is less than two percent. Because all paints contain some amount of binders, the painted surfaces should be heat treated at about 300°F for about 3 to 4 hours. Pre-heating will prevent off-gassing from the absorber coating and condensation of volatile components on the lower cover glass. The condensation of paint binders on the lower glass cover reduces the transmission of solar radiation through the glass.

Black paints are inexpensive and relatively easy to apply, but there are some disadvantages. While there is high absorptivity of the solar radiation with a black paint, there is also high emissivity. High emissivity results in high radiation heat loss from the absorber. There are special black selective surface materials which result in high absorptance of solar radiation and low emittance of thermal radiation. Selective surfaces convert a large fraction of solar radiation to heat and suppress radiation heat loss so that more useful heat is delivered from the collector when compared to one with a black painted surface. Various selective surfaces are being developed by many collector manufacturers and in the next few years some are likely to be used for flat-plate collectors.

CORROSION

Table 5-1 lists a galvanic series of metals and alloys in aqueous solutions. In the list, the metals at the top are easily corroded, while those at the bottom are not easily corroded in an aqueous solution.

Table 5-1

Galvanic Series of Metals and Alloys in Aqueous Solutions

Easily Corroded	Magnesium
	Zinc
	Aluminum
	Steel or Iron
	Cast Iron
	Lead
	Tin
	Brass
	Copper
	Bronze
	Chromium-Iron
	Silver
Difficult to Corrode	Graphite
	Gold
	Platinum

Magnesium is sometimes used for sacrificial anodes to protect zinc, iron, brass, copper, and bronze but this must not be done if aluminum pipes or absorbers are used in a water system.

Electrolytes, other than hardness and alkalinity, promote corrosion. The presence of calcium, bicarbonate, metaphosphate, and monohydrogen phosphate ions assists in corrosion control. The presence of silica, organic color, and borax is beneficial. Factors which aid corrosion of metals in aqueous solutions are dissolved oxygen, acids, sulfides, tin, copper, cobalt, nickel, and lead as well as the presence of magnesium (in aluminum systems), chloride, sulfate, nitrate, carbonate, and hydroxide ions. Water circulated through solar collectors should not be permitted to become acidic because corrosion is more rapid in acidic water solutions than in neutral or slightly basic solutions. The water should be drained if it becomes acidic.

Corrosion is minimized when the dissolved oxygen concentration is zero. The free oxygen in an air-tight system collector loop will be lost as some corrosion takes place on the pipes in the system.

A corrosion inhibitor that could be added to the water in the collector loop is presented in Table 5-2. The recommended concentration in water is 1.5 percent by weight, giving a pH of between 7.5 and 8.0. The inhibitor cost is about 60 cents per pound, and with the suggested mix, the cost is about $70 per 1000 gallons of water.

Automotive grade ethylene glycol solutions also contain corrosion inhibitors. If the composition of the corrosion inhibitor is not given, further information should be sought. One should be especially careful with aluminum tubes and pipes. In general, a 30 percent concentration of automotive grade antifreeze which contains corrosion inhibitors is needed to obtain sufficient protection against rust and corrosion.

Table 5-2

Composition of a Suggested Corrosion Inhibitor Additive

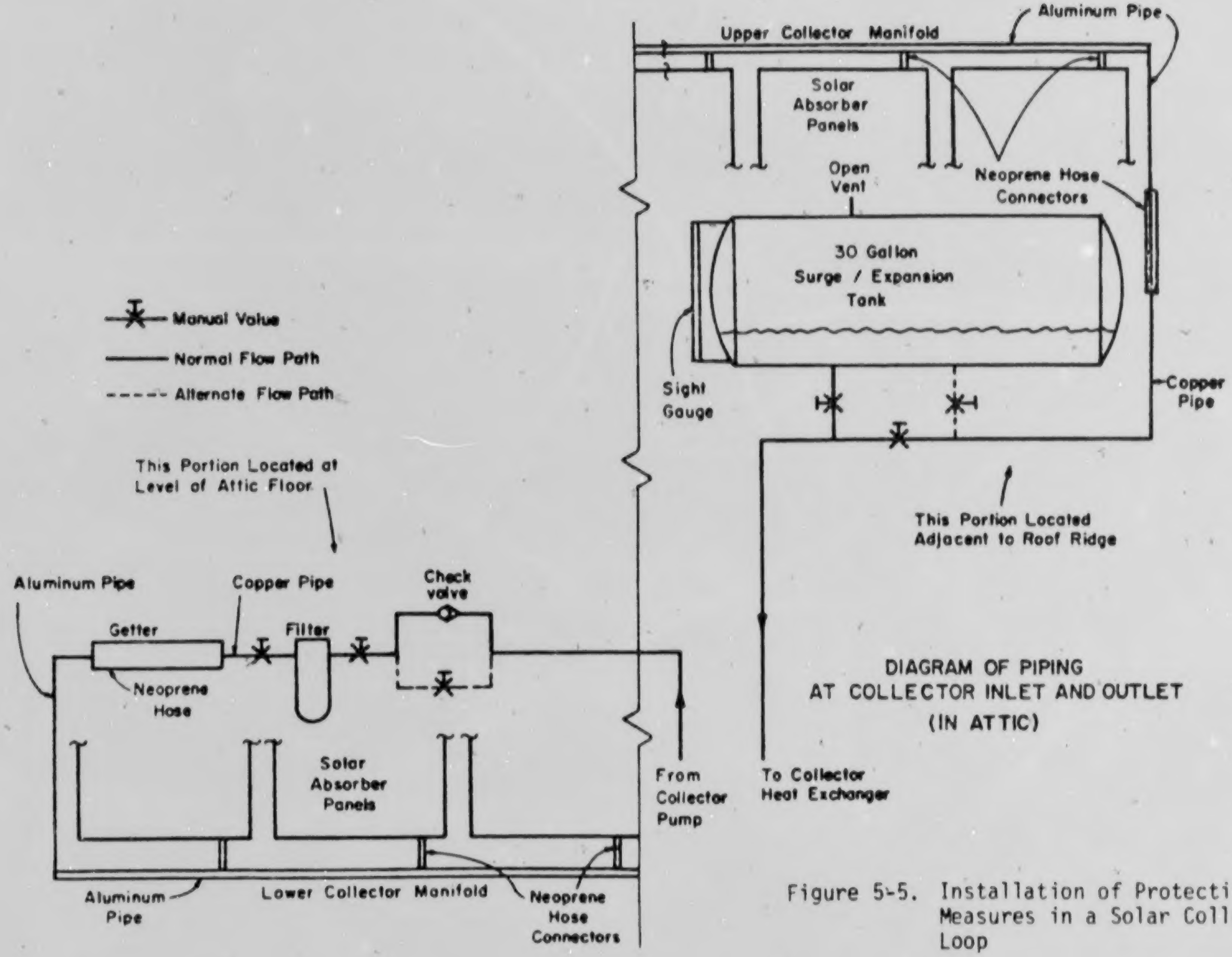
Concentration	Optimum Percent by Weight
Mercaptobenzothiazole (technical grade, 92% min)	15.1
Sodium borate decahydrate $Na_2B_4O_7 \cdot 10\ H_2O$ (borax)	75.7
Anhydrous disodium phosphate Na_2HPO_4	9.2
	100.0

Removal of small particles by filtration will reduce erosion of the small tubes in the absorber of the collector. A filter which will remove particles greater than 50 microns is satisfactory, but the pressure drop across the filter may be too large if the flow velocity is high. Fifty micron filters may be used initially in the system, and later a change to about 350 micron size may be made.

Heavy metal ions (such as copper and iron) can react with aluminum by displacement of the aluminum and deposition of the other metal. To minimize such ion exchange, an ion getter can be used. An ion getter with an aluminum window screen placed in the pipeline has been used satisfactorily. Various protection devices in a collector loop are shown in Figure 5-5. A filter, ion getter, and non-metallic hoses connecting pipes of different materials are shown in the figure.

LIQUIDS

Experience indicates that an ethylene glycol concentration of 10 to 20 percent is adequate to prevent pipe and tubing from bursting when



Upper Collector Manifold
Aluminum Pipe
Solar Absorber Panels
Open Vent
Neoprene Hose Connectors
30 Gallon Surge / Expansion Tank
Sight Gauge
Copper Pipe
Manual Value
Normal Flow Path
Alternate Flow Path
This Portion Located at Level of Attic Floor
This Portion Located Adjacent to Roof Ridge
Aluminum Pipe
Copper Pipe
Check valve
Getter
Filter
Neoprene Hose
Solar Absorber Panels
From Collector Pump
To Collector Heat Exchanger
DIAGRAM OF PIPING AT COLLECTOR INLET AND OUTLET (IN ATTIC)
Aluminum Pipe
Lower Collector Manifold
Neoprene Hose Connectors

Figure 5-5. Installation of Protective Measures in a Solar Collector Loop

exposed to temperatures well below the freezing point of the mixture. If the liquid in the system is static and flow at low temperatures is not required, it is unnecessary to use glycol concentrations as high as indicated in freezing point tables. However, it is important that the pipes leading to a collector are protected from freezing so that flow is always possible. Otherwise, the liquid in the collector may boil even in midwinter and, if the pipes are frozen, the tubes in the absorber could burst from excessive pressure.

Adequate freeze protection for a water collector can be obtained with antifreeze concentrations that are less than those required in an automobile radiator, as the purpose of the antifreeze is to prevent damage to the collector, but not to prevent the formation of ice crystals. In Table 5-3, the temperatures and percent ethylene glycol concentration in water (by volume) have proven to result in a slushy condition which, while very dense, does not result in damage to the tubes. If the corrosion inhibitor additive in the antifreeze is to be utilized, the minimum concentration should be about 30 percent.

Table 5-3

Concentration of Ethylene Glycol Required for Freeze Protection

Percent Ethylene Glycol by Volume in Water	Minimum Temperature for Freeze Protection, °F*
0	32
5	26
10	16
15	2
20	-18

*Flow will not be possible below these temperatures

Thermal decomposition of ethylene glycol takes place at about 329°F. The rate of thermal decomposition is very low in this temperature range and, unless significantly higher temperatures are encountered, thermal decomposition of the antifreeze additive will not be a problem. A maximum temperature of 300°F is suggested in the absence of dissolved oxygen in the solution, and lower temperatures are recommended to extend the service life of the liquid solution.

In the presence of air, ethylene glycol degrades more readily than without air. A portion of the degradation product results in an acidic solution which promotes corrosion. If simultaneous exposure to oxygen and elevated temperatures of the ethylene glycol solution cannot be avoided, then the temperatures must be moderated. The allowable maximum temperature depends upon the degree of aeration and the desired service life of the solution. A temperature of 250°F may be acceptable when the only source of air is a vent or vacuum breaker line. Anti-oxidants are helpful in some applications. Ethylene glycol concentrations greater than 60 percent by weight are not used because the minimum freezing point is achieved at 60 percent.

The price of two other heat transfer liquids are given in Table 5-4. Dowtherm J is currently being used in the Phoenix solar heated house in Colorado Springs, Colorado. Therminol 55 is used in high temperature solar collectors. Some of the physical properties of the two liquids are given in Table 5-5.

Dowtherm J is non-corrosive toward all metals or alloys commonly used in solar systems, such as steel, copper, aluminum, and stainless steel alloys.

Oxidation is a problem when heat transfer fluids at high temperatures are exposed to the atmosphere in open systems. Significant oxidation

Table 5-4

Cost of Two Heat Transfer Liquids

Quantity and Container Size	Price per Gallon	
	Dowtherm J	Therminol 55
5 gallon cans		16.10
1 drum*	4.60	2.90
5 drums	4.10	2.90
1 - 9 drums		2.90
20 drums	3.99	2.60
10 - 59 drums		2.60
60 drums or more		2.20
4,000 gallon tank truck	3.77	
40,000 pounds or more		1.50
*55 gallon drums (each contains 400 pounds of Therminol 55)		

Table 5-5

Some Physical Properties of Dowtherm J and Therminol 55

Property	Dowtherm J	Therminol 55
Operating temperature range, °F	-100 to 575	-5 to 600
Pour point, °F		-40
Boiling point, °F	358	635
Flash point, °F	145	355
Fire point, °F	155	410
Auto ignition temperature, °F	806	675

can cause the fluid viscosity to increase and insoluble material to be formed. The insolubles will decrease the heat transfer rate at the tube walls, increase film temperatures, and accelerate thermal degradation of the tube walls.

Dowtherm J is resistant to both thermal degradation and oxidation. To prevent oxidation in open systems, the temperature of Dowtherm J liquid should not exceed 300°F.

FLAT-PLATE AIR-HEATING SOLAR COLLECTORS

A cross-section of a typical air-heating solar collector is shown in Figure 5-6. The conversion of solar radiation to heat is exactly the same as for liquid-heating collectors. Because air is used as the heat transfer medium, the air passage is a duct, instead of tubes in liquid collectors, and the top surface of the duct forms the absorber plate.

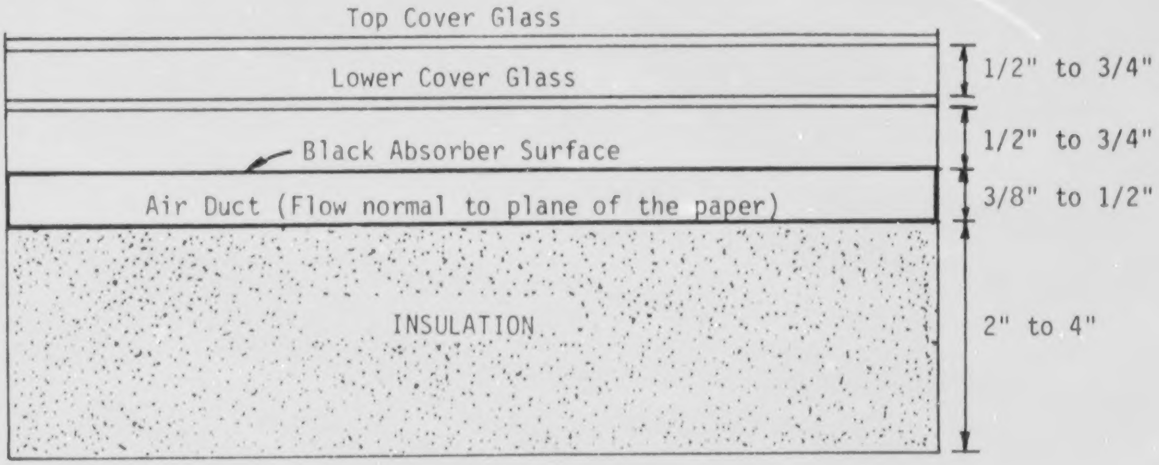

Top Cover Glass
Lower Cover Glass
1/2" to 3/4"
Black Absorber Surface
1/2" to 3/4"
Air Duct (Flow normal to plane of the paper)
3/8" to 1/2"
INSULATION
2" to 4"

Figure 5-6. Cross-Section of an Air Heating Solar Collector

Air-heating solar collectors are less efficient than liquid-heating solar collectors at high fluid temperatures. However, the efficiency of the total solar system is comparable with liquid systems.

Air-heating collectors have a number of advantages compared with liquid-heating collectors. There are no problems with freezing in the collector or overheating the air. Corrosion problems are also minimized. Galvanized ducts do not require corrosion protection but insulation is required. A system disadvantage is that a larger storage volume is needed but an advantage is that stratification of temperature in storage permits air collectors to operate at best efficiency throughout the day.

The long-term durability of solar collectors is still unknown. However, there is one air system using glass plate absorbers in the collector which has operated continuously since 1957. It is generally expected that solar air heating collectors will have a long "lifetime" of use, although more data from operating systems are needed before conclusive statements can be made.

SOLAR COLLECTOR EFFICIENCY

STEADY-STATE COLLECTOR EFFICIENCY

Solar collector efficiency is the fraction of the solar energy intercepted by the collector that is converted to heat and delivered to the building. Factors which influence solar collector efficiency include absorber surface coating, number and type of transparent covers, fluid flow distribution through the collector, fluid temperature, outdoor air temperature, and the intensity of solar radiation on the collector glass area. The collector efficiencies for several different solar collectors are shown in Figure 5-7 and the selected collectors are described in Table 5-6.

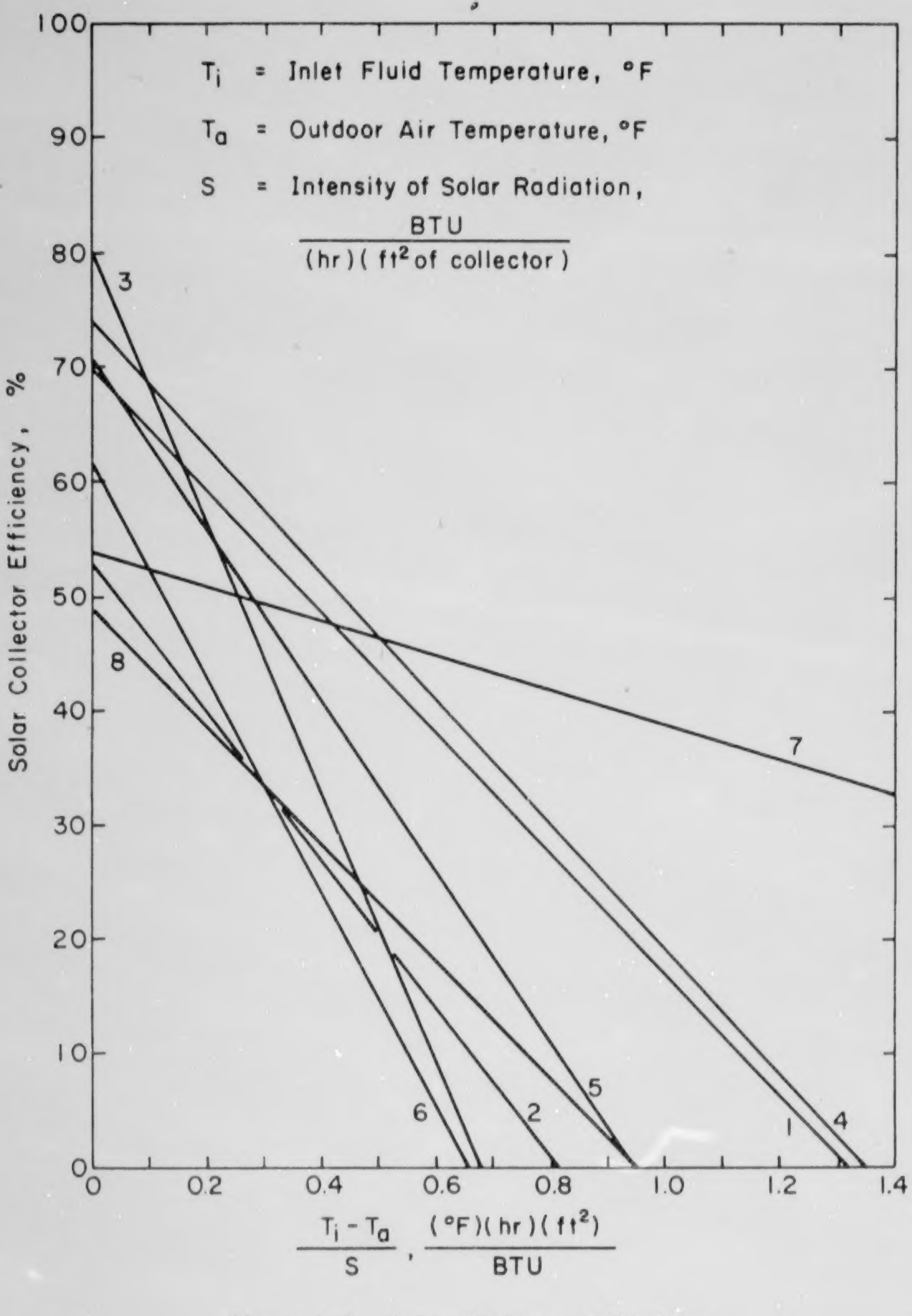


Figure 5-7. Solar Collector Efficiency

Table 5-6

Description of Solar Collectors Plotted in Figure 5-7

Absorber Material	Collector Number from Figure 5-7	Manufacturer and Remarks	Absorber Surface Coating	Transparent Covers		Stagnation Temperature °F *
				Number	Material	
Aluminum	1	NASA/Honeywell	black nickel	2	glass	466
Aluminum	2	MSFC	black nickel	2	Tedlar	313
Aluminum	3	NASA/Honeywell	black paint	1	glass	274
Aluminum	4	NASA/Honeywell (mylar honeycomb)	black paint	2	glass	475
Aluminum	5	NASA/Honeywell	black paint	2	glass	355
Aluminum	6	PPG	black paint	2	glass	268
Glass	**7	Owens (evacuated tube)	selective surface	1	glass	1,150
Steel	8	Solaron (data furnished by manufacturer) Heat transfer fluid is air	black paint	2	glass	355

* Values are calculated assuming that incident solar radiation, S, is 300 Btu/(ft^2)(hr) and that ambient temperature, T_a, is 70°F.

** With the exception of solar collectors number 7 and 8, the absorber plates are tubes-in-plate.

The efficiencies of solar collectors are often expressed as a function of inlet fluid temperature and ambient air temperatures. While use of inlet fluid temperature in the efficiency curves presented by manufacturers is acceptable for liquid heating collectors, it is not a useful variable to express the efficiency changes for air-heating collectors. This is because the inlet temperature to an air-heating collector in a system is always near room temperature, while the inlet fluid temperature for a liquid-heating collector varies considerably during the day. The comparison of liquid-heating collectors can be based on efficiency curves similar to Figure 5-7, but comparisons of liquid- and air-heating collectors are more difficult. Unfortunately, no easy method has been determined to compare the performance characteristics of air-and liquid-heating collectors, but a recent study of two similarly sized systems on comparable houses at the same location and during the same time periods shows that the air-heating system collected more useful energy than did the liquid system. The reader is cautioned, however, that more data are needed before definitive conclusions about collector and system performance can be made.

The efficiency of an air-heating solar collector increases with air flow rate, but large air flow rates require large blowers and large electricity consumption in proportion to the solar energy collected. A recommended air flow rate for air collectors is about 2 cfm per square foot of collector.

For liquid-heating solar collectors, the liquid (water-ethylene glycol mixture) flow rate should be between 0.6 and 1.2 gallons per hour per square foot of solar collector area. Only a small gain in energy collection, hence collector efficiency, is realized by circulating more than

1.2 gal/(hr)(ft^2). On the other hand, when less than 0.6 gal/(hr)(ft^2) is circulated, the efficiency is significantly reduced.

DAILY COLLECTOR EFFICIENCY

The efficiencies shown on Figure 5-7 are not appropriate for long-term collector efficiency, such as daily efficiency, because the fluid and ambient temperatures as well as the solar radiation continuously change during the day. The efficiencies shown on Figure 5-7 are for steady-state conditions and, while they are useful for comparing different collectors (one fluid type), they are not directly useful to determine the quantity of energy collected by a system during the day. An average daily efficiency of collectors in a system is more useful for that purpose.

The daily efficiencies of the collectors for CSU Solar House I is shown in Table 5-7, for each month of the year. The second column in the table lists the efficiencies based on total measured solar radiation. The fourth column lists the efficiencies based on solar radiation on the collector during the periods when the collectors delivered useful energy. During the year the average daily efficiency varies from 15 to 25 percent, depending on the solar and climatic conditions and the operation of the system. The higher temperatures of storage water required for operating the cooling system during the summer lowered the collector efficiency when compared to winter conditions.

While average daily collector efficiency is dependent upon many design factors of the system, a daily efficiency from 25 to 35 percent can be expected with most collectors now available commercially. Because the collector is a very important component of a solar system, and the

Table 5-7

Mean Daily Collector Efficiencies for Each Month of the Year

	Average Daily Efficiency Based on Solar Radiation	Average S (MJ/day)	Average Daily Efficiency Based on When the Collectors Delivered Useful Energy
September	22.5	1106	31.5
October	21.2	849	20.4
November	19.6	780	31.2
December	23.8	967	33.3
January	24.6	999	33.0
February	24.6	1274	36.9
March	18.9	1395	34.5
April	15.2	1513	32.3
May	15.0	1217	35.9
June	14.5	1375	34.3
July	15.6	1474	22.9
August	15.0	1429	27.2

performance of the entire solar system is the important factor in system economics, individuals are discouraged from making their own collector unless the person has considerable experience and knowledge about solar collectors.

STAGNATION TEMPERATURE

An important factor in collector performance is the capability to withstand the highest temperature achieved in the collector when there is no fluid flow and the solar energy is a maximum. The highest temperature is the stagnation temperature, which could develop when there is electrical power failure and the pump or blower stops, and most certainly during installation when there is no fluid (in liquid heating collectors) in the collector. Stagnation temperatures listed in Table 5-6 are very high, particularly for the evacuated tube collector.

COLLECTOR ARRAY

Most of the previous sections concerned collector modules and, in general, several modules are required in a solar system to provide the energy to meet the heating and cooling needs. Collector modules may be assembled in a number of different ways to form an array of collectors, and one possible arrangement for liquid collectors is shown on Figure 5-4.

A recommended arrangement for an air-heating collector array with internal as well as external manifolding is shown in Figure 5-8. Variations to the scheme shown are, of course, possible. A very important

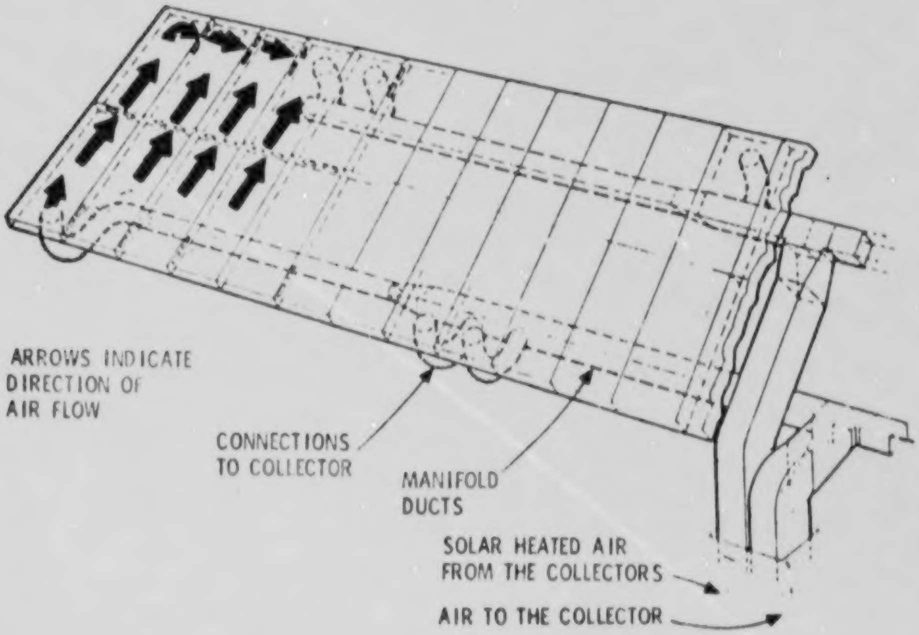

ARROWS INDICATE DIRECTION OF AIR FLOW
CONNECTIONS TO COLLECTOR
MANIFOLD DUCTS
SOLAR HEATED AIR FROM THE COLLECTORS
AIR TO THE COLLECTOR

Figure 5-8. Typical Arrangement of Internally Manifolded Collector Modules in an Array

factor in any scheme is to be sure that joints in the duct system do not leak.

Collector arrays, for both liquid and air heating systems, should be leak tested during assembly if possible. While leaks in liquid systems are easy to detect, leaks in air systems are not as readily determined. Care during installation of collectors, with joints in pipes and ducts, is advised. The cost of labor for careful assembly is a small fraction of the cost of labor for disassembly and making repairs.

Joints in piping, particularly from the headers to the collector modules, may be made with flexible hoses. Because neoprene or rubber hoses will require replacement periodically, sufficient thought should be given to facilitate the replacement. Other piping connections and valve locations should be given similar consideration. Connections from the headers to the absorber plates of the collectors cannot be rigid coupling because there is considerable expansion and contraction of the absorber plates and the headers during the day as the collectors are heated and cooled.

TRAINING COURSE IN
THE PRACTICAL ASPECTS OF
SIZING, INSTALLATION, AND OPERATION OF SOLAR HEATING AND COOLING SYSTEMS
FOR
RESIDENTIAL BUILDINGS

MODULE 6

THERMAL STORAGE SUBSYSTEMS

SOLAR ENERGY APPLICATIONS LABORATORY
COLORADO STATE UNIVERSITY
FORT COLLINS, COLORADO

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INTRODUCTION

Heat storage is necessary for solar heating, cooling, and service hot water heating installations. While there is some heat storage in the structure and contents of a building, it is not an appreciable fraction of required storage. Practical methods of heat storage and basic guidelines for sizing are presented in this module.

OBJECTIVE

The objective is to describe different heat storage media and provide guidelines for sizing the storage unit for specific requirements. The subobjectives for the trainees are to be able to:

1. Select a thermal storage unit for a particular type of solar system,
2. Size and locate the thermal storage unit,
3. Schedule and install the thermal storage unit in the system,
4. Recognize potential maintenance features of thermal storage units.

METHODS OF HEAT STORAGE

Heat may be stored for use in heating and cooling residential buildings in the forms of latent heat, sensible heat, and combination of latent and sensible heats.

LATENT HEAT STORAGE

Latent heat can be stored by melting a solid, such as wax, into a liquid. The stored heat is released when the temperature drops and the heat which is released is supplied to the conditioned space. If a suitable material is used, solar heat at temperatures provided by collectors can be used to melt a solid and to store the heat during the day, and then be made to release the heat when the liquid reverts back to solid form. A very small temperature difference is sufficient to change the phase from solid to liquid or liquid to solid. The use of ice to cool an "ice box" and to cool liquids illustrates the use of latent heat for cooling.

There are also two principal advantages to latent heat storage. Because very large quantities of heat can be stored and released per pound of material, it takes less volume to store the heat required by the system. A latent heat storage unit using paraffin or wax would require about one-fourth as much volume as a water tank to store an equivalent amount of heat. A second advantage is that the temperature remains nearly constant during phase changes. A constant operating temperature for hot storage or cold storage is particularly advantageous for operating a chiller.

There are, however, some disadvantages with latent heat storage units. Many known latent heat materials will last only a few years and must be replaced. As of the time of this writing, suitable materials are also expensive when compared to water or pebble-bed storage units. More time is needed for development of practical latent heat storage units.

Table 6-1 is a listing of some available latent heat storage materials.

Table 6-1

Latent Heat Storage Materials

Name	Melting point °F	Heat of Fusion	
		Btu/lb	Btu/cu ft
Hydrated Inorganic Salts			
Sodium chromate	67.8	78.4	7400
Manganese nitrate	79.4	60.4	6570
Ortho Phosphoric acid	84.8	61.6	7010
Lithium nitrate	85.8	127	18200
Calcium chloride	86.4	73.2	7570
Glauber Salt	90.4	102.3	9320
Disodium phosphate	94.2	121.0	11550
Manganous nitrate	95.8	50.4	6240
Zinc nitrate	97.2	56.1	7180
Calcium nitrate	108.6	61.1	6900
Thiosulfate (Hypo)	119.4	40.7	4710
Nickelous nitrate	134.0	65.6	8330
Cobaltous nitrate	134.7	54.4	8300
Cadmium nitrate	139.1	45.7	6950
Sulfur trioxide	144.0	137	16750
Magnesium nitrate	182.2	68.8	9380
Hydrazine hydrochloride	198.8	95.7	7700
Magnesium chloride	244.0	72.7	9000
Anhydrous Inorganic Salts			
Arsenic tribromide	89.4	16.0	
Meta Phosphoric Acid	108.5	46.2	
Phosphoric acid	158	67.4	
Antimony trichloride	164	24.0	
Antimony tribromide	205.5	16.6	
Aluminum bromide	208.3	18.2	
Ammonium acid sulfate	291	53.5	
Ammonium nitrate	337	27.4	
Potassium thiocyanate	350	48	
Waxes and Organic Solids			
Anthracine	205	45.2	3480
Anthraquinone	545	67.8	6030
Naphthaline	176	64.9	4620
Naphthol	203	70.0	5280
Bees wax	143	76.2	4500
Stearic acid (tallow)	169	85.4	4500
Amorphous paraffin wax	166	99.0	4900

SENSIBLE HEAT STORAGE

Sensible heat is stored when the temperature of a storage medium increases. Water and pebbles are the most common materials used for sensible heat storage because they are low in cost and readily available. Any thermally and chemically stable solid or liquid may be used if the costs are justifiable.

The amount of heat required to raise the temperature of one pound of matter one degree is the heat capacity of the material. Heat capacities for common materials are listed in Table 6-2, in terms of both mass and volume.

Table 6-2
Heat Capacity Values

Material	Heat Capacity	
	Btu/lb °F	Btu/ft^3 °F
Wood	0.6	45
Steel	.11	54
0.75 to 1.5 inch rock	0.2	20
Water	1.0	62

It will be noted that water has three times the heat capacity as compared to rock for the same volume. This means that a pebble-bed storage unit would be three times larger than a water tank to store the same amount of heat.

SOLAR HEAT STORAGE SIZE

Precise heat storage sizing is not required for solar systems, but there is an economical size for a given installation. A very large volume of storage does not result in providing more solar heat to the building enclosure as compared to an adequately sized unit. Thus a disproportionately large storage capacity relative to a fixed collector area is not useful.

A solar system that is to provide a major fraction of the annual heating load for a building should provide for overnight heating from the solar energy collected during a normal winter day. If the previous day was cloudy, then the system will depend upon the auxiliary unit to provide heating. A large solar collector area which provides more heat than is needed by the building will have excess heat that can be stored in a large storage volume. Such a system could store enough heat for use over several days if there is no sunshine. The cost of the system increases, however, because of the larger collector area and storage volume. The most practical size to consider is a solar system that will provide for 20 to 30 hours of heating during normal winter days. The recommended size of storage relative to collector area is one to two gallons of water for a liquid system, or one-half to one cubic foot of pebbles per square foot of collector area for an air system. A solar system for a residential building with 500 square feet of collectors should have a storage unit with about 700 gallons of water capacity, or 300 cubic feet of pebbles. The installed cost of such a storage unit would range from $500 to $1,000.

HEAT LOSS FROM STORAGE

If the heat storage unit is placed inside the building enclosure, the heat loss from the unit will be to the building interior. In the heating season the heat is effectively utilized, but in the summer the heat loss from storage will add to the cooling load. By placing the storage unit within a vented and insulated room, use of the heat loss from storage can be effectively controlled during winter and summer.

LOCATION OF SOLAR HEAT STORAGE

Solar heat storage units may be located above or below grade and either inside the heated building or outdoors. It is recommended that the storage unit be placed within the building enclosure whenever possible and close to other solar equipment. An indoor storage location has the advantage that it is protected from moisture and cold,and the heat loss from the storage unit will assist in heating the building in winter. The disadvantages of locating the heat storage unit indoors are that heat loss to the building adds to the cooling load during the summer and a finite amount of relatively expensive space must be provided.

When a storage unit is placed underground, the insulation must be of a kind which will not absorb moisture. Materials such as neoprene foam or styrofoam could be suitable. The tank should be placed below the frost line unless a concrete lined pit is provided for the tank, pumps, and other equipment. The pumps which circulate the storage water should be placed at a level to prevent vapor locking at the impellers.

WATER HEAT STORAGE

Water should be used for heat storage if a liquid is used as the heat transport medium in the solar collectors. If an antifreeze solution is needed in the collectors, it is advisable to separate the fluid circulation loops with a heat exchanger between the collector and storage loops. If freezing is not of concern, water from storage may be circulated through the collectors without a heat exchanger and the storage water is pumped directly to the heating coils or the absorption cooling unit.

Four conditions must be avoided when using water for heat storage. They are:

1. Freezing, in cold climates
2. Boiling, with resultant build-up of pressure in the system
3. Corrosion of the storage tanks and pipes
4. Leakage

Because it is prohibitively expensive to provide enough antifreeze in a water storage tank to protect against freezing, it is recommended that the water storage tank be placed inside the building or underground below the frost line. A storage tank inside the building is preferable to one underground. Heat loss from underground tanks is not recoverable for useful purposes. Also repairs, if necessary, are easier on indoor tanks.

Boiling can occur in the storage tank and provisions should be made to prevent damage to the system or to the contents of the building. While it is an uncommon occurrence for well-designed systems during the heating season, frequent boiling may be expected during the summer if the heat is not used to operate a chiller. The steam that is produced can be easily vented outside the building to prevent pressure build-up in the tank and to "dump" the heat from the system. A pipe from the top of the tank to the outdoors with a low pressure relief valve is sufficient. For a non-pressurized system, a pressure relief valve is not required, but a float controlled valve to provide make-up water in the storage tank should be provided. Frequent boiling of storage water will cause build-up of mineral deposits with consequences in corrosion unless water softeners are used.

A high temperature shut-off control on the collector pump may be used with some collectors to avoid boiling. Many collectors, however, are not designed to withstand the high temperatures which result from no flow for an extended period; thus the practice of stopping circulation is dependent upon the type of collector that is selected.

Corrosion is a potential problem whenever water is contained in a metal tank and the probability of corrosion greatly increases with temperature. Fiberglass lining to protect against corrosion and water softeners will increase the life of the tank but add costs to the system.

Corrosion often occurs at the pipe connections to the tank. If dissimilar metals are used, galvanic corrosion will result. Therefore, neoprene rubber hoses should be used to connect copper pipes to steel tank fittings.

Water leakage must be prevented because it can damage tank insulation and other materials near the tank. Because there is difficulty in locating a leak after insulation is applied, the tank should be leak tested with all fittings in place before insulation is applied.

PRINCIPLES OF WATER STORAGE TANK OPERATION

Useful heat is stored between a minimum threshold temperature and a maximum critical temperature, which is usually the boiling point. The minimum temperature is the lowest useful temperature that can provide heat to the load. For space cooling this is about 180°F; for space heating, 90°F; and for service water heating, 60°F. The maximum critical temperature is the boiling point for a vented tank and could be a higher temperature for a pressurized tank. The pressures that will build up in the tank at various temperatures above boiling are listed in Table 6-2. If the maximum allowable pressure in the tank is 30 psi, for example, the maximum allowable storage tank temperature is 274°F.

Table 6-3

Maximum Critical Temperature and Maximum Allowable Tank Pressure

Storage Tank Pressure (psi)	Maximum Temperature (°F)
0	212
10	239
20	259
30	274
40	287
50	298

The top of the storage tank will generally be hotter than the bottom, and the magnitude of the temperature difference is a function of tank height and diameter. Any temperature stratification achieved is useful because the lowest temperature possible is pumped to the collector, which improves the performance of the collectors, and the highest temperature available is delivered to the heating coils to heat the house. This arrangement is illustrated in Figure 6-1.

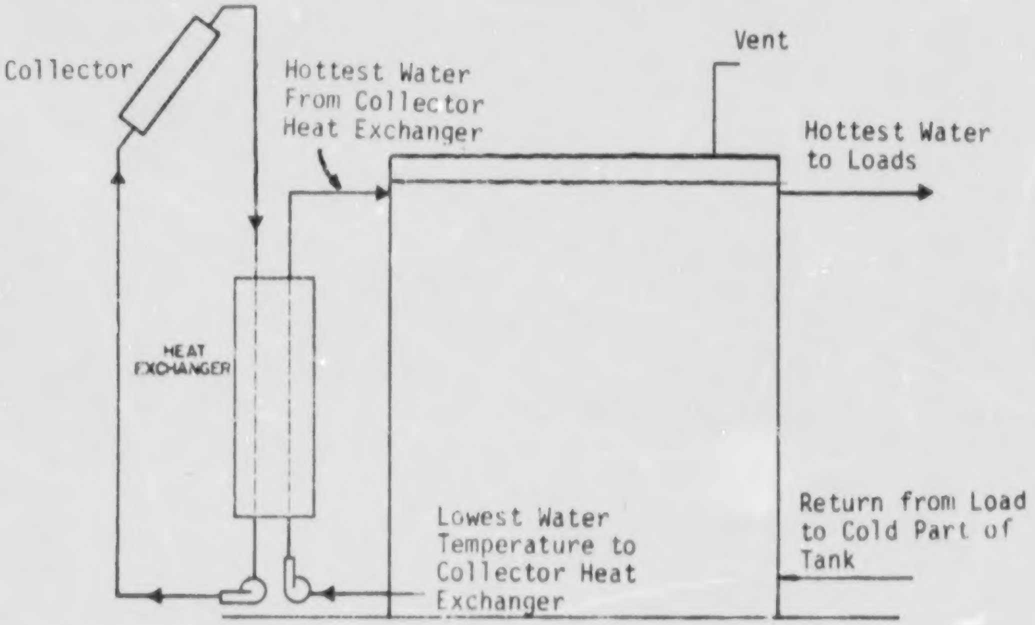
Collector
Hottest Water From Collector Heat Exchanger
Vent
Hottest Water to Loads
HEAT EXCHANGER
Lowest Water Temperature to Collector Heat Exchanger
Return from Load to Cold Part of Tank

Figure 6-1. Operation of a Water Heat Storage Tank

WATER TANK INSTALLATION

Storage units are normally the first of the solar components placed in the building during construction. Because of their size, it is advantageous to install the tanks before the building is enclosed. Exterior buried storage units may be installed after the building is erected and, economically, the excavation and concrete work for the storage unit should be scheduled with the building foundation work. Water storage tanks should be movable from the building because of the possibility of future replacement. If a large access for the tank is not possible in the building design, several smaller tanks may be nested together, or the tank may be of a type that can be assembled and disassembled.

The storage tank should be well insulated (R-20 or better) on all surfaces, including the bottom. The bottom is more difficult to insulate because it must withstand the filled tank load (about 70 pounds per square foot for each foot of depth, i.e., 420 pounds per square foot for a six foot tall tank). Also, the insulation should preferably be moisture-resistant or provided with ventilation air spaces, as shown in Figure 6-2, which illustrates a practical tank bottom insulation arrangement. The side and top insulation, which may be fiberglass wool or foam insulation, may be installed later along with other equipment.

The pipe connections should be provided with the tank. Leak testing of all tank connections is advisable before insulation is applied. Not only are leaks difficult to detect after being covered with insulation, the heat loss through wet insulation is so large that it is equivalent to no insulation. Standard plumbing precautions should be exercised by placing shut-off valves at strategic locations to isolate the tank, heat exchanger, pumps, and other appurtenances. Drain connections should be provided with a valve and hose connection. Neoprene (high temperature)

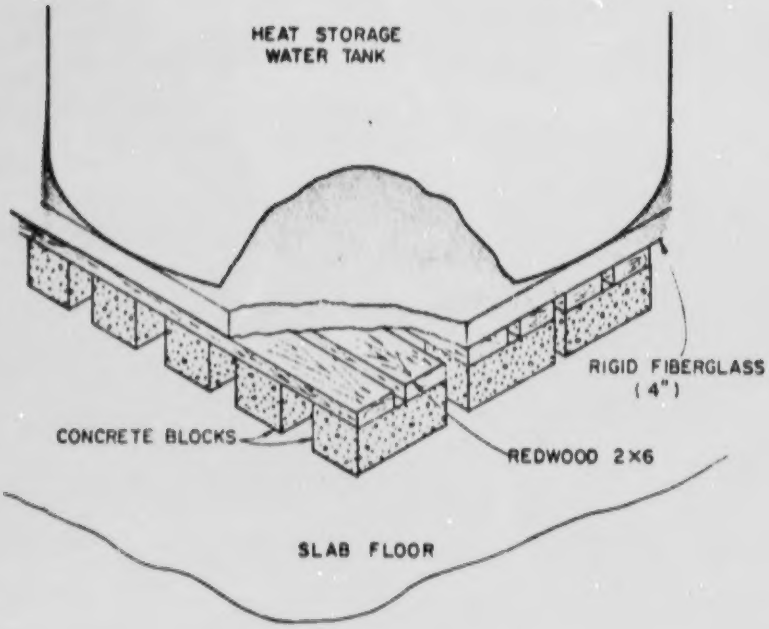
HEAT STORAGE
WATER TANK
RIGID FIBERGLASS
(4")
CONCRETE BLOCKS
REDWOOD 2×6
SLAB FLOOR

Figure 6-2. Bottom Insulation and Support Scheme for Water Storage Tanks

rubber hose connection between the tank and the piping is advised to prevent strain at the tank connection and to protect against corrosion where dissimilar metals are used. A bulk head fitting, as illustrated in Figure 6-3, is an alternative way of providing connections to the tank.

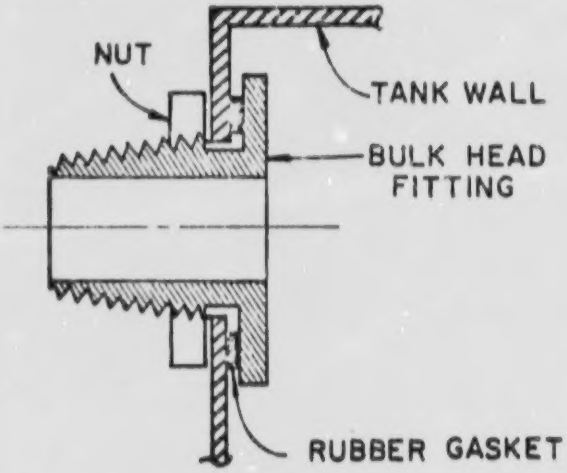
NUT
TANK WALL
BULK HEAD
FITTING
RUBBER GASKET

Figure 6-3. Bulk Head Type Connection

WATER STORAGE TANK MATERIALS

Water storage tanks may be made of concrete, fiberglass, or steel. The costs of these three tanks are nearly equal, at about one dollar per gallon of capacity, including the insulation.

Concrete Tanks

Concrete tanks are durable but difficult to install. Some prefabricated units, such as septic tanks and large diameter pipes, may be assembled and used as water storage tanks or they may be cast in place.

Although conductivity of heat through concrete is less than through metals, concrete tanks should be insulated to reduce heat loss. A high temperature sealant on the interior surface or a watertight liner is recommended to prevent seepage of water through the tank.

Fiberglass Tanks

Fiberglass tanks are corrosion resistant, but have limitations with regard to temperature. Although some fiberglass will withstand temperatures over 212°F, many commonly fabricated tanks will not tolerate temperatures above 160°F. At high temperatures, the bonding resins in the fiberglass soften and the material begins to flow.

Glass-Lined or Galvanized Steel Tanks

Steel tanks are readily available and suitable for water storage. Glass-lined or galvanized steel tanks, while costing more, may be used effectively to reduce the rate of corrosion inside the tank.

PEBBLE-BED STORAGE

Solar heated air is passed directly through the pebble-bed from top to bottom. As the air passes through the pebbles, heat is transferred from the air to the rocks so that the rock temperature rises. The cool air which leaves the bottom of the pebble-bed is returned to the collectors to be reheated. The top of the pebble-bed will be warmer than the bottom because of hot air supply from the collectors. After sundown and discontinuance of air circulation, the pebble-bed will maintain this temperature stratification because heat conduction through the bed from one pebble to another is small.

The stored heat is delivered to the building by circulating room air through the pebble-bed in the direction opposite that of the storing cycle, that is, from the bottom toward the top of the pebble-bed. As the cool air flows through the spaces between the pebbles, it is heated and the warm air is recirculated to the rooms. The bottom of the pebble-bed is always at the lowest temperature, usually room temperature, and because the coldest air is delivered to the collectors, the collectors operate at maximum efficiency.

The hot end, or collector supply end, of the pebble-bed is preferably at the top to prevent heat loss to the floor. If the layout requires the hot end at the bottom, two inches of rigid fiberglass board should be placed under the unit to reduce heat loss to the floor.

PEBBLE-BED INSTALLATION

A maximum depth of about six feet of pebbles is recommended for acceptable floor loading and air pressure loss. The pressure drop also depends upon size and uniformity of the pebbles. At a typical air velocity of about 20 feet per minute through five feet of 0.75 to 1.5 inch gravel, the pressure drop will be about 0.3 inch water gauge.

As shown in Figure 6-4, the pebbles are supported on a wire screen, such as "expanded metal", which in turn is supported on bond beam blocks for maximum free area to air flow in the lower plenum. Coverage of the bottom by the supporting blocks should be about 50 percent for light-weight screen support. If a heavy mesh woven or welded wire screen is used, the block spacing can be greater.

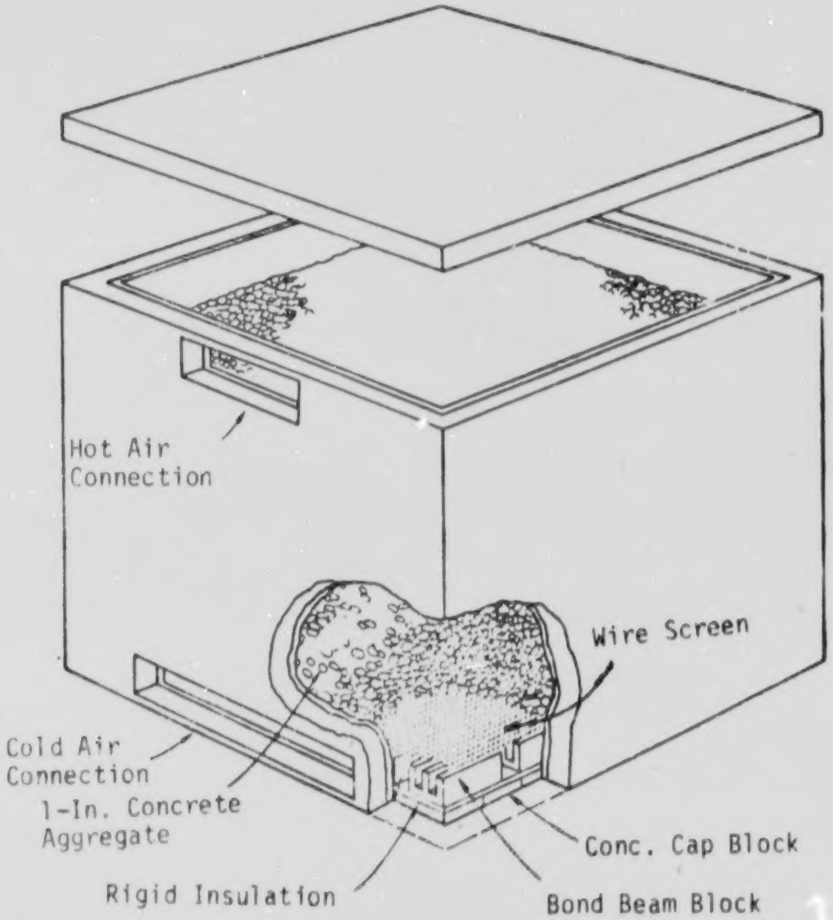
Hot Air
Connection
Wire Screen
Cold Air
Connection
1-In. Concrete
Aggregate
Conc. Cap Block
Rigid Insulation
Bond Beam Block

Figure 6-4. Pebble-Bed Heat Storage Unit

Although horizontal flow has occasionally been used in pebble-beds, heat exchange effectiveness has been lower than in vertical flow beds. By channelling of air flow across the top of the bed, because of the tendency for warm air to flow through the upper part and cool air through the bottom, the effectiveness of stratification is impaired. If a horizontal arrangement cannot be avoided, vertical baffles should be provided to prevent a "short circuit" when the rock settles. This arrangement is illustrated in Figure 6-5.

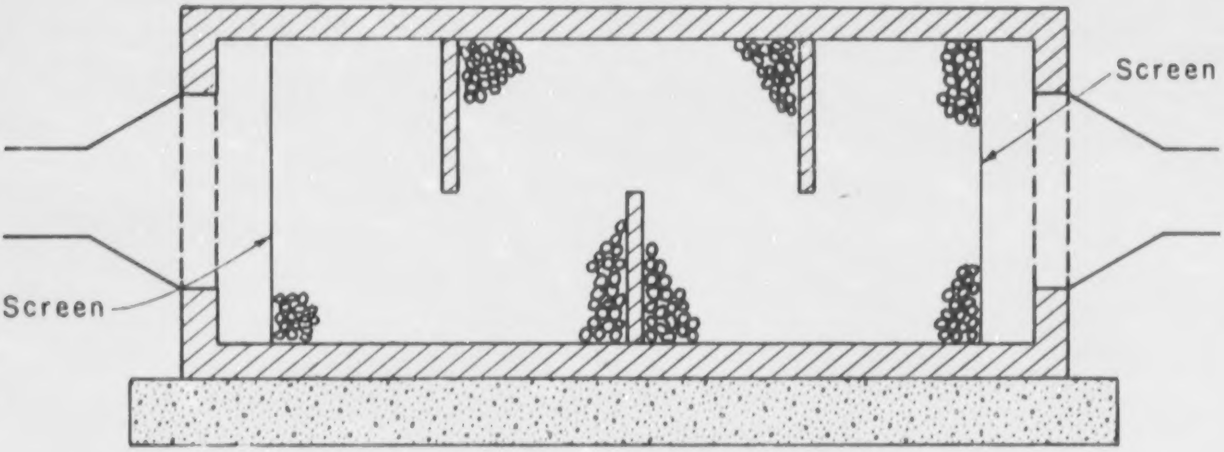

Figure 6-5. Horizontal Flow Pebble-Bed

PEBBLE-BED CONTAINERS

Pebble-beds may be contained in wood frame boxes, concrete block walls, or cylindrical steel bins. Wood frame boxes can be built in place where access is limited. Steel wire or tie rods should be placed across the box to prevent the sides from bulging under the pressure of the pebbles. Framing should be of construction grade 2 x 4's on one-foot centers. One-half inch plywood can be used on both sides of the 2 x 4 studs and the space filled with three and one-half inch fiberglass roll insulation.

Steel bins make convenient pebble-bed containers. They can be assembled by bolting curved sections together on the job site. A durable caulking compound must be used at the joints to prevent air leakage. Two-inch foam insulation should be cut into segments and placed around the outside of the bin.

Concrete block may also be used for the pebble-bed walls. Steel reinforcement rods three-eighths inch (3/8") in diameter should be placed across the bed every two to three feet to support the walls. Two-inch rigid fiberglass insulating board should be used to line the inside of the block walls.

A concrete bin is relatively economical when constructed with basement walls. Two additional walls in one corner of the basement level, with suitable openings, form the rock bin. Rigid insulation on the inside or outside can be added to reduce thermal losses. After filling, an insulated cover on a 2 x 4 frame can then be installed.

ROCKS FOR THE PEBBLE-BED

Any type of rock suitable for concrete aggregate can be used in the pebble-bed. Size uniformity is important in order to provide proper air flow through the pebble bed and graded gravel should not be used. One-inch concrete aggregate is screened so that the sizes vary from 0.75 to 1.5 inches and the aggregate is suitable for the pebble-bed.

The pebbles should be free of fines, and concrete aggregate is normally acceptable. The bed should be filled by using a chute so that fracturing will be minimized and damage to the walls and bottom of the unit will be avoided.

TRAINING COURSE IN
THE PRACTICAL ASPECTS OF
SIZING, INSTALLATION, AND OPERATION OF SOLAR HEATING AND COOLING SYSTEMS
FOR
RESIDENTIAL BUILDINGS

MODULE 7

SERVICE HOT WATER SYSTEMS

SOLAR ENERGY APPLICATIONS LABORATORY
COLORADO STATE UNIVERSITY
FORT COLLINS, COLORADO

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INTRODUCTION

The oldest and simplest domestic use of solar energy is for heating water. Solar hot water heaters were used in the United States at least 75 years ago, first in southern California and later in southern Florida. Although the use of solar water heaters in these regions declined during the last 40 years, use in Australia, Israel, and Japan has risen rapidly, particularly in the last 15 years.

In its simplest form, a solar water heater comprises a flat-plate water heating collector and an insulated storage tank positioned at a higher level than the collector. These components, connected to the cold water main and the hot water service piping in the dwelling, provide most of the hot water requirements in a sunny climate. Nearly all of the solar hot water systems used in the United States have been of this type.

OBJECTIVE

The objective is to choose a particular arrangement suitable for a given location, size the system for a given collector type and hot water requirement, install the system, and be confident of satisfactory operation. From the contents of this module the trainee should be able to:

1. Identify the types of domestic hot water systems available,
2. Select a domestic hot water system for a particular location and application,
3. Integrate a domestic hot water system into a space heating system,

4. Install and put into operation a domestic hot water system,
5. Maintain a domestic hot water system.

TYPES AND CHARACTERISTICS OF SOLAR HOT WATER HEATERS

Most of the solar water heaters that have been experimentally and commercially used can be placed in two main groups:

1. Circulating types, involving the supply of solar heat to a fluid circulating through a collector and storage of hot water in a separate tank
2. Non-circulating types, involving the use of water containers that serve both as solar collector and storage.

The circulating group may be divided into the following types and sub-types:

1. Direct heating, single-fluid types in which the water is heated directly in the collector, by:
    a. Thermosiphon circulation between collector and storage
    b. Pumped circulation between collector and storage
2. Indirect heating, dual-fluid types in which a non-freezing medium is circulated through the collector for subsequent heat exchange with water, when:
    a. Heat transfer medium is a non-freezing liquid
    b. Heat transfer medium is air.

DIRECT HEATING, THERMOSIPHON CIRCULATING TYPE

The most common type of solar water heater, used almost exclusively in non-freezing climates, is shown in Figure 7-1. The collector, usually

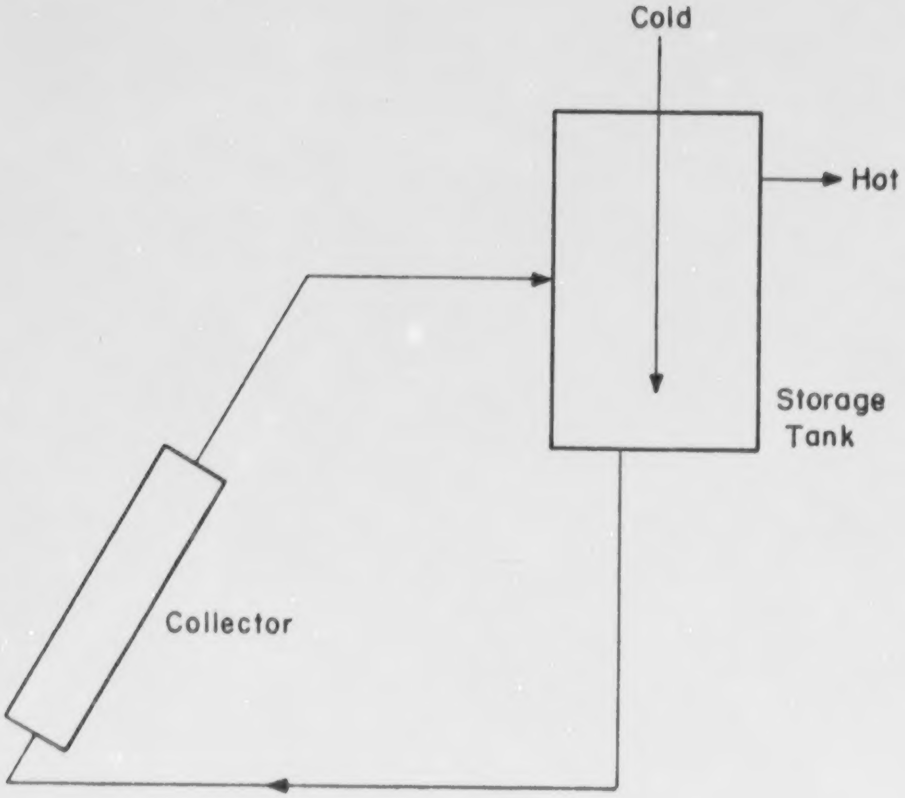


Figure 7-1. Direct Heating Thermosiphon Circulation Type of Solar Water Heater

single glazed, may vary in size from about 30 square feet to 80 square feet, whereas the insulated storage tank is commonly in the range of 40 to 80 gallons capacity. The hot water requirements of a family of four persons can usually be met by a system in the middle of this size range, in a sunny climate. Operation at supply line pressure can be provided if the system is so designed. With a float valve in the storage tank or in an elevated head tank, unpressurized operation can be utilized if the system is not designed for pressure. In the latter case, gravity flow from the hot water tank to hot water faucets would have to be accepted, or an automatic pump would have to be provided in the hot water line to supply pressure service. Plumbing systems and fixtures in the United States normally require the pressurized system.

Location of the tank higher than the top of the collector permits circulation of water from the bottom of the tank through the collector and back to the top of the tank. The density difference between cold and hot water produces the circulating flow. Temperature stratification in the storage tank permits operation of the collector under most favorable conditions, water at the lowest available temperature being supplied to the collector and the highest available temperature being provided to service. Circulation occurs only when solar energy is being received, so the system is self-controlling. The higher the radiation level, the greater the heating and the more rapid the circulating rate will be. In a typical collector under a full sun, a temperature rise of 15°F to 20°F is commonly realized in a single pass through the collector.

To prevent reserve circulation and cooling of stored water when no solar energy is being received, the bottom of the tank should be located above the top header of the collector. If the collector is on a house roof, the tank may also be on the roof or in the attic space beneath a sloping roof.

Although seldom used in cold climates, the thermosiphon type of solar water heater (storage tank above collector), can be protected from freezing by draining the collector. To avoid draining the storage tank also, thermostatically actuated valves in the lines between collector and storage tank must close when freezing threatens, a collector drain valve must open, and a collector vent valve must also open. The collector will then drain,and air will enter the collector tubes. Water in the storage tank, either inside the heated space or sufficiently well insulated to avoid freezing, does not enter the collector during the period when sub-freezing temperatures threaten. Resumption of operation requires closure of the drain and vent valves and opening of the valves in the circulating line. The possibility of control failure or valve malfunction makes this complex system unattractive in freezing climates.

DIRECT HEATING, PUMP CIRCULATION TYPES

If placement of the storage tank above the collector is inconvenient or impossible, the tank may be located below the collector and a small pump used for circulating water between collector and storage tank. This arrangement is usually more practical than the thermosiphon type in the United States, because the collector would often be located on the roof with a storage tank in the basement. Instead of thermosiphon circulation when the sun shines, a temperature sensor actuates a small pump which circulates water through the collector-storage loop. A schematic arrangement is shown in Figure 7-2. To obtain maximum utilization of solar energy,

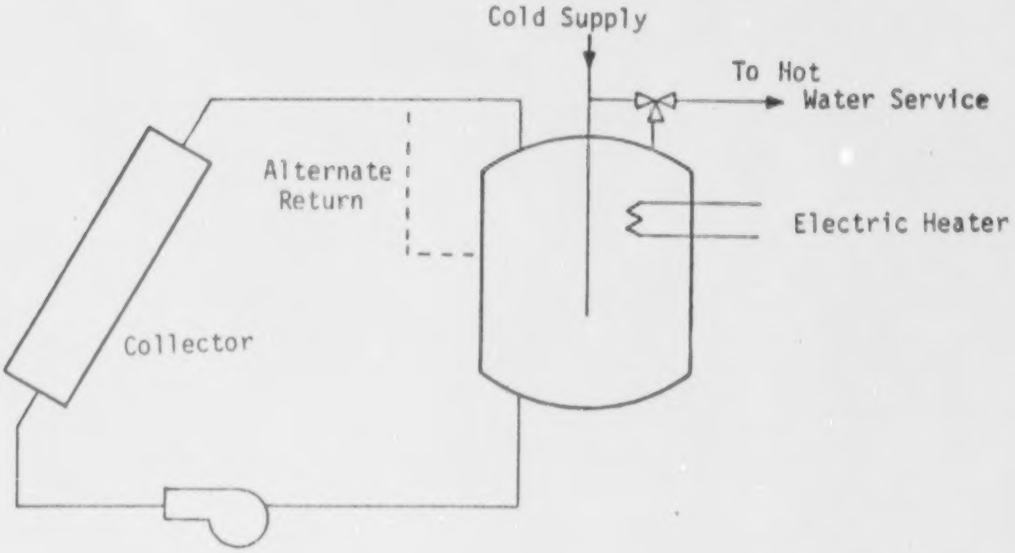


Figure 7-2. Direct Heating, Pump Circulation Type of Solar Water Heater

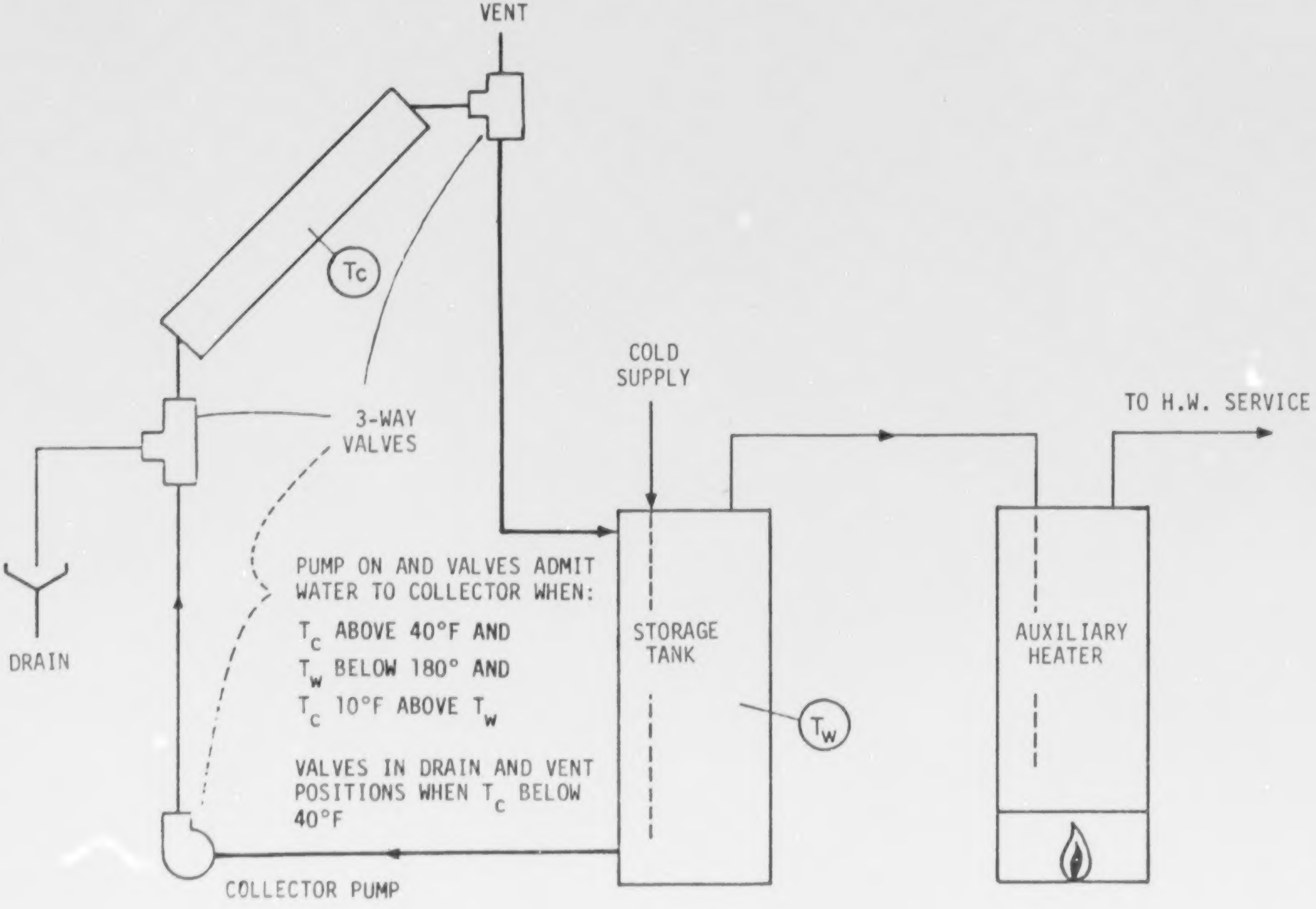
control is based on the difference in water temperature at collector outlet and bottom of storage tank. Whenever this difference exceeds a preset number of degrees, say 10°F, the pump motor is actuated. The sensor at the collector outlet must be located close enough to the collector so that it is affected by collector temperature even when the pump is not running. Similarly, the sensor in the storage tank should be located in or near the bottom outlet from which the collector is supplied. When the temperature difference falls below the preset value, the pump is shut off and circulation ceases. To prevent reverse thermosiphon circulation and consequent water cooling when no solar energy is being received, a check valve should be located in the circulation line.

If hot water use is not sufficient to maintain storage tank temperature at normal levels (as during several days of non-use), boiling may occur in the collector. If a check valve or pressure-reducing valve prohibits back flow from the storage tank into the main, a relief valve must be provided in the collector-storage loop. The relief valve will permit the escape of steam and prevent damage to the system.

DIRECT HEATING, PUMP CIRCULATION, DRAINABLE TYPES

If the solar water heater described above is used in a cold climate, it may be protected from freeze damage by draining the collector when sub-freezing temperatures are encountered. Several methods can be used. Their common requirement, however, is reliability, even when electric power may not be available. One method is shown in Figure 7-3.

Drainage of the collector in freezing weather can be accomplished by automatic valves which provide water outflow to a drain (sewer) and the inflow of air to the collector. The control system can be arranged so that whenever the circulating pump is not in operation, these two


VENT
T_c
COLD SUPPLY
TO H.W. SERVICE
3-WAY VALVES
DRAIN
STORAGE TANK
T_w
AUXILIARY HEATER
COLLECTOR PUMP

PUMP ON AND VALVES ADMIT WATER TO COLLECTOR WHEN:

T_c ABOVE 40°F AND

T_w BELOW 180° AND

T_c 10°F ABOVE T_w

VALVES IN DRAIN AND VENT POSITIONS WHEN T_c BELOW 40°F

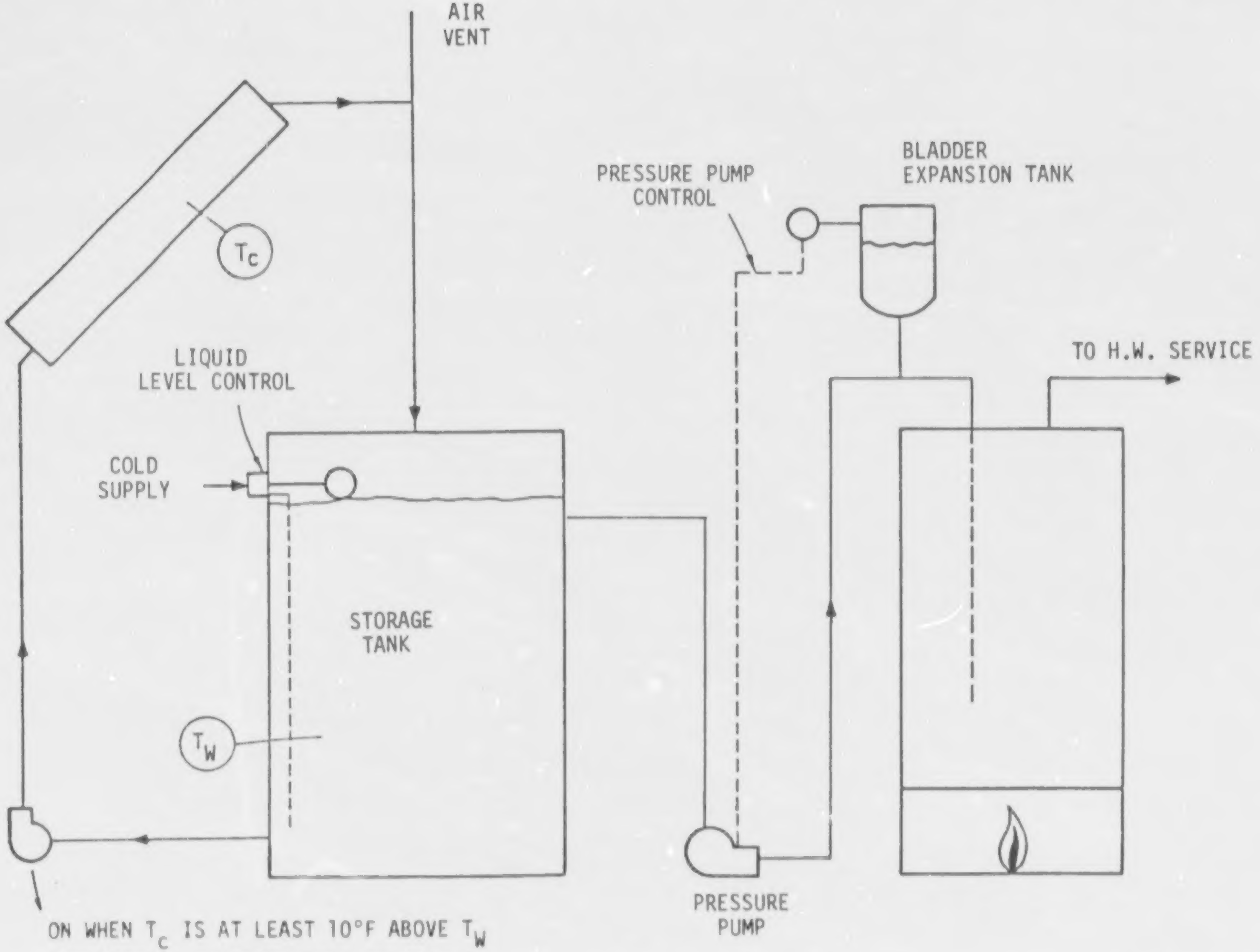
Figure 7-3. Solar Water Heater with Freeze Protection by Automatic Collector Drainage

valves are open. To assure maximum reliability, the valves should be mechanically driven to the drain position (by springs or other means), rather than electrically, so that in the event of a power failure, the collector can automatically drain.

The drainage system shown in Figure 7-3 is actuated by the temperature sensor, T_c, in the collector. When the sensor indicates a possibility of freezing, it can open the drainage and vent valves, thereby providing protection. The temperature sensor can be of the vapor pressure type, with capillary tube connections to mechanical valve actuators, or of the electrical type where the valves are held open by electrical means, automatically closing either when electrical failure occurs, or at low temperatures.

Another possibility for drainage of the collector is based on use of a non-pressurized collector and storage assembly as shown in Figure 7-4. A float valve in the storage tank controls the admission of cold water to the tank, and a pump in the hot water distribution system can furnish the necessary service pressure. With this design, the solar collector drains into the storage tank whenever the pump is not operating, as air enters the collector through a vent.

Start-up of any of the vented collector systems must permit the displacement of air from the collector. In either the line-pressure system or the unpressurized system, the entry of water into the collector (from the shut-off valve or pump) forces air from the collector tubes as long as the vent remains open. The vent valve design can be of a type which automatically passes air but shuts off when water reaches it.


AIR VENT
T_C
LIQUID LEVEL CONTROL
COLD SUPPLY
STORAGE TANK
T_W
PRESSURE PUMP CONTROL
BLADDER EXPANSION TANK
TO H.W. SERVICE
PRESSURE PUMP

ON WHEN T_C IS AT LEAST 10°F ABOVE T_W
OFF WHEN T_W IS ABOVE 180° OR WHEN T_C IS NOT AT LEAST 10°F ABOVE T_W

Figure 7-4. Unpressurized Vented Solar Water Heater System

CIRCULATING TYPE, INDIRECT HEATING

As can be inferred from the above discussions of needs and means for collector drainage in freezing climates, costs and hazards are involved with those systems. The drainage requirement can be eliminated by the use of a non-freezing heat transfer medium in the solar collector, and a heat exchanger (inside the building) for transfer of heat from the solar heat collecting medium to the service water. The collector need never be drained, and there is no risk of freezing and damage. Corrosion rate in the wet collector tubes is also decreased when intermittent admission of oxygen is not required.

Liquid Transfer Media

Figure 7-5 illustrates a method for solar water heating with a liquid heat transfer medium in the solar collector. The most commonly used liquid is a solution of ethylene glycol (which is common automobile radiator antifreeze) in water. A pump circulates this unpressurized solution, as in the direct water heating system, and delivers the liquid to and through a liquid-to-liquid heat exchanger. Simultaneously, another pump circulates domestic water from the storage tank through the exchanger, back to storage. The control system is essentially the same as that in the design employing water in the collector directly. If the heat exchanger is located below the bottom of the storage tank, and if the pipe sizes and heat exchanger design are adequate, thermosiphon circulation of water through the heat exchanger can be used. A small expansion tank needs to be provided in the collector loop, preferably near the high point of the system, with a vent to the atmosphere.

To meet most code requirements, the heat exchanger must be of a design such that rupture or corrosion failure will not permit flow from

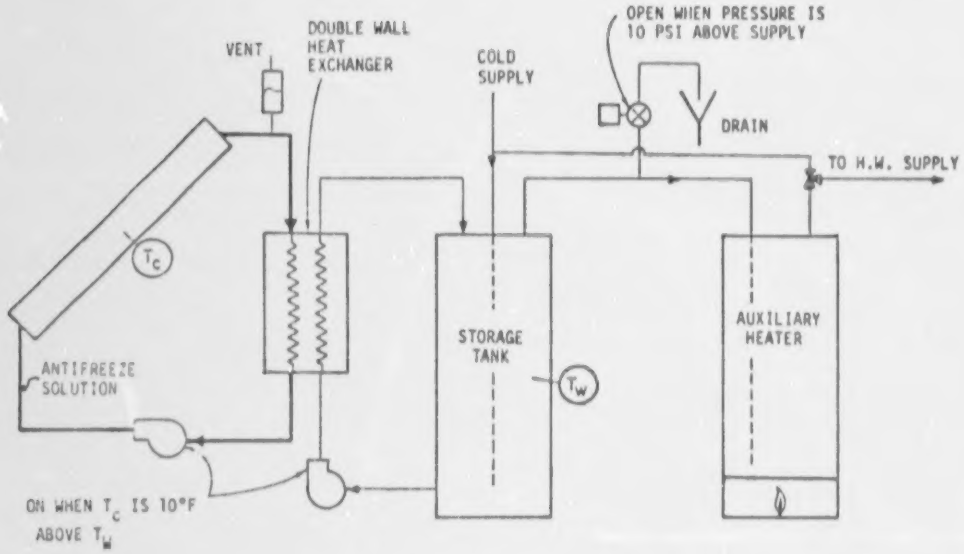

VENT
DOUBLE WALL HEAT EXCHANGER
COLD SUPPLY
OPEN WHEN PRESSURE IS 10 PSI ABOVE SUPPLY
DRAIN
TO H.W. SUPPLY
T_c
STORAGE TANK
T_W
AUXILIARY HEATER
ANTIFREEZE SOLUTION
ON WHEN T_c IS 10°F ABOVE T_W

Figure 7-5. Dual Liquid Solar Hot Water Heater

the collector loop into the domestic water, even if pressure on the water side of the exchanger drops below that on the antifreeze side. A conventional tube-and-shell exchanger would therefore not usually be acceptable. Similarly, a coil inside the storage tank, through which the collector fluid is circulated, would not be satisfactory. Parallel tubes with metal bonds between them, so that perforation of one tube could not result in liquid entry into the other tube, would be a suitable design. A finned tube air-to-liquid heat exchanger could also be used by circulating the two liquids through alternate rows of tubes, heat transfer being by conduction through the fins.

Although aqueous solutions of ethylene glycol and propylene glycol appear to be most practical for solar energy collection, organic liquids such as Dowtherm J and Therminol 55 may be employed. Price and viscosity are drawbacks, but chemical stability and assurance against boiling are advantages over the antifreeze mixtures.

Solar Collection in Heated Air

In a manner similar to that described immediately above, solar energy can be employed in an air heating collector with subsequent transfer to domestic water in an air-to-water heat exchanger. Figure 7-6 illustrates a method for employing this concept. A solar air heater is supplied with air from a blower, the air is heated by passage through the collector, and the hot air is then cooled in the heat exchanger through which domestic water from a storage tank is either being pumped or is circulating by thermosiphon action. Air from the heat exchanger is recirculated to the collector. Differential temperature control (between collector and storage) is employed as in the other systems described. Advantages of the air

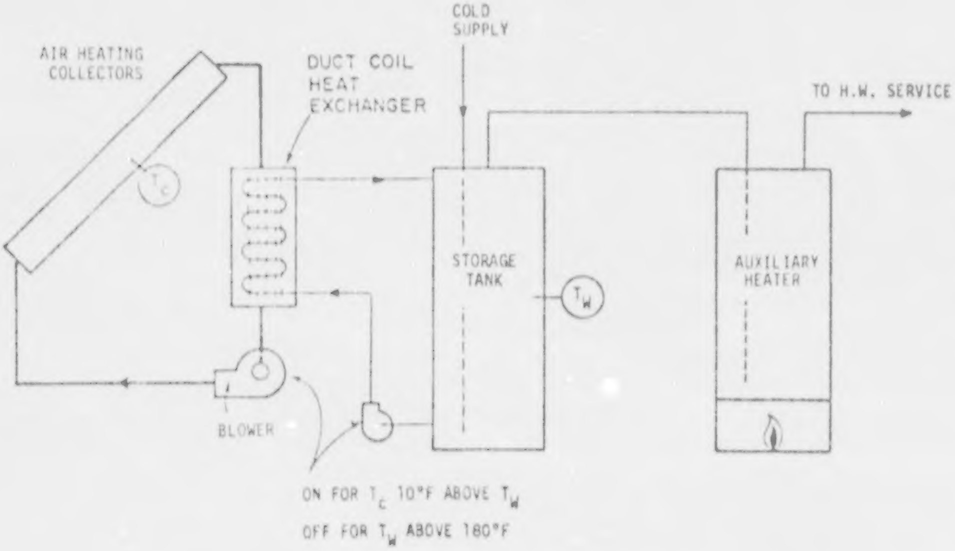

AIR HEATING COLLECTORS
DUCT COIL HEAT EXCHANGER
COLD SUPPLY
TO H.W. SERVICE
T_C
STORAGE TANK
T_W
AUXILIARY HEATER
BLOWER
ON FOR T_C 10°F ABOVE T_W
OFF FOR T_W ABOVE 180°F

Figure 7-6. Solar Hot Water Heater with Air Collectors

heat transfer medium are the absence of corrosion in the collector loop, freedom from liquid leakage, and freedom from boiling and loss of collector fluid. Disadvantages are the larger conduit between collector and heat exchanger, higher power consumption for circulation, and slightly larger collector surface requirements.

NON-CIRCULATING TYPE

Although probably of little potential interest in the United States, a type of solar water heater extensively used in Japan involves heat collection and water storage in the same unit. The most common type comprises a set of black plastic tubes about six inches in diameter and several feet long in a glass-covered box. Usually mounted in a tilted position, the tubes are filled each morning with water in which solar heat is collected throughout the day. The filling can be accomplished by a float-controlled valve and a small supply tank. Late in the day, heated water can be drained from the tubes for household use. In typical Japanese installations, non-pressurized hot water service is thus provided. Heat loss from the system is sufficiently high at night that hot water is usually not available until several hours after sunrise.

AUXILIARY HEAT

A dependable supply of hot water requires the availability of auxiliary heat for supplementing the solar source. The numerous methods of providing auxiliary heat vary in cost and effectiveness. A general principle for maximizing solar supply and minimizing auxiliary use is the avoidance of direct or indirect auxiliary heat input to the fluid entering the solar collector. If auxiliary heat is added to the solar hot water storage tank, so that the temperature of the liquid supplied to the collector is increased above that which only the solar system would provide, efficiency is reduced because of higher heat losses from the collector. Thus, auxiliary heat should be added at a point beyond (downstream from) the solar collector-storage system. Figures 7-3 and 7-4 show a conventional gas-fired hot water heater being supplied with hot water from the solar tank (whenever a hot water tap is opened). Any deficiency in temperature is made up by fuel in the thermostatted conventional heater. Alternatively, a "fast response", in-line heater can be employed. It is evident that auxiliary heat supply in these designs cannot adversely affect the operation of the solar system.

Another way in which auxiliary heat can be used without reducing solar collection efficiency is by electric resistance heaters in the upper portion of the solar storage tank, as shown in Figure 7-2. Temperature stratification in the tank, accomplished by bringing cold water from the main into the bottom and by circulating through the collector from the bottom of the tank to the upper portion of the tank, thereby prevents auxiliary heat from increasing the temperature of the water supplied to the collector. Water returning from the collector may be brought into the tank well below the level of the resistance heater (as shown by the dashed line), so that the hot supply is always available at the thermostatted temperature. In effect, the two tanks shown in Figures 7-3 and 7-4 are combined into one, with temperature stratification providing a separation. The total amount of storage is, of course, reduced unless the one tank is increased in size. If relatively high temperature water is desired, there may be an undesirable influence of auxiliary supply on collector efficiency because of some mixing in the tank.

Although the description of the above systems refers to direct circulation of water through the collector, the same factors apply to the systems involving heat exchange with antifreeze solutions or air circulating through the collector. In all cases, auxiliary heat should be supplied downstream from the solar storage tank, regardless of whether the water itself is circulated through the collector or whether heat is exchanged between the domestic water and a solar heat transfer fluid.

LOCATION OF COLLECTORS

If the slope and orientation of a roof is suitable, the most economical location for a solar collector in a residential water heating system is on the south-facing portion of the roof. The cost of a structure to support the collector is thereby eliminated, and pipe or duct connections to the conventional hot water system are usually convenient. In new dwellings, most installations can be expected on the house roof. Even in retrofitting existing dwellings with solar water heaters, a suitable roof location can usually be provided.

If the mounting of collectors on the roof is impractical, for any of several reasons, a separate structure adjacent to the house may be used. A sloping platform supported on a suitable foundation can be the base for the collector. Pumps, storage tank, and heat exchanger, if used, can be located inside the dwelling. Effective insulation on ducts and piping must be provided, however, so that cold weather operation will not be handicapped by excessive heat losses. In cold climates, collectors in which water is directly heated must be located so that drainage of the collector and exterior piping can be dependably and effectively accomplished.

TEMPERATURE STRATIFICATION IN SOLAR HOT WATER TANK

As in a conventional hot water heater, the temperature in the upper part of a solar hot water tank will normally be considerably higher than at the bottom. The lower density of hot water permits this stratification, provided that turbulence at inlet and outlet connections is not excessive. The supply of relatively cold water from the bottom of the tank to the collector permits the collector to operate at its highest possible efficiency under the prevailing ambient conditions. With a circulation rate such that a temperature rise through the collector of 15°F to 20°F occurs, the lower part of the storage tank is furnished to the collector for maximum effectiveness. If not much hot water is withdrawn from the tank during a sunny day, the late afternoon temperature at the bottom of an 80 gallon tank connected to a 40-to 50-square foot collector may be well above 100°F -- even approaching the temperature in the top of the tank. Collection efficiency thus varies throughout the day, depending not only on solar availability but also on the temperature of water supplied to the collector from the tank bottom.

TEMPERATURE CONTROL LIMIT

In addition to the differential temperature control desirable in most solar water heating systems (which sense temperature difference between collector and storage), protection against excessive water temperature may be necessary. Several possible methods can be used. In nearly all types of systems, whether direct heating of the potable water or indirect heating through a heat exchanger, a thermostatically controlled mixing valve can be used to provide constant temperature water for household use.

Figure 7-7 illustrates one method by which this type of temperature control can be accomplished. Cold water is admitted to the hot water line immediately downstream from the auxiliary heater in sufficient proportion to secure the desired preset temperature. The solar hot water tank is allowed to reach any temperature attainable, and the auxiliary heater furnishes additional energy only when the auxiliary tank temperature drops below the thermostat set point. Maximum solar heat delivery is thus achieved, and no solar heat needs to be discarded except that which might sometimes be delivered when the main storage (preheat) tank is at the boiling point. Any additional solar heat collected under that condition would be dumped through a pressure relief valve, steam escaping to the surroundings. Figure 7-5 shows an optional second mixing valve for control of delivery temperature by admitting regulated amounts of solar heated water into the flow from the auxiliary heater.

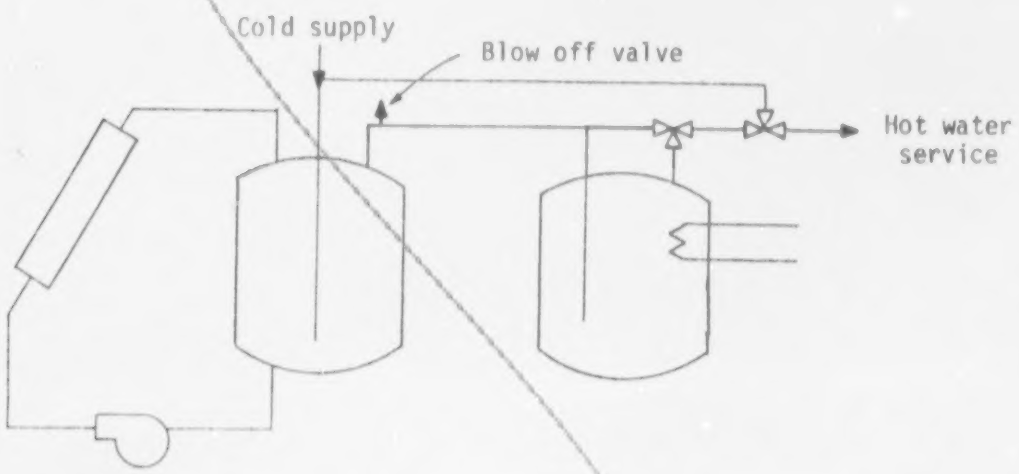


Figure 7-7. Direct Solar Water Heating with Mixing Valve

A steam vent from the solar hot water system involving a dual liquid design, with heat exchange, should normally be in the hot water loop rather than the collector loop. Loss of collector fluid by vaporization is thereby avoided. It is necessary, however, in this design, that the collector tubes and associated piping be capable of withstanding pressure at least as high as developed when the steam vent valve in the storage loop is actuated. If, for example, the blow-off valve in the storage circuit is set for 50 psi, and if the collector loop containing 50 percent ethylene glycol normally operates at a temperature 20°F above the storage tank temperature, pressure in the collector loop would also be about 50 psi when the storage tank vent is actuated. (Approximate equality of pressure is due to similarity between boiling point elevation and temperature difference in the heat exchanger.)

An alternative to the high pressure collector capability described above is available in the form of an organic heat transfer fluid having a high boiling point. Downtherm J or Therminol 55 have boiling points above 300°F, so if one of these fluids is used, the development of pressure in the collector loop would not occur, even when the storage system is venting steam at 50 psi. This option appears considerably more practical than the pressurized collector required with aqueous systems if the dual-liquid design is utilized.

Still another option for high-temperature protection is available if the collector is used as a heater for a high-boiling organic liquid or for air. To prevent the storage tank from reaching a temperature higher than desired, a limiting thermostat in that tank can be used simply to discontinue circulation of the heat transfer fluid (organic liquid or air) through the collector and heat exchanger. No additional heat is therefore dissipated in the form of collector heat loss. The collector temperature rises substantially, frequently above 300°F, but if properly designed, the collector suffers no damage. This system is probably the safest and most dependable of those herein described. With a reliable limit switch in the storage tank, there can be no dangerous pressure developments anywhere in the system. In addition, there is no loss of water (in the form of steam) even when there is no use of hot water for long periods.

If the hot water/cold water mixing valve downstream from the auxiliary heater is not used, a temperature limit control in the solar storage tank can be set at the maximum desired temperature of service hot water. Water, therefore, cannot be delivered at any temperature higher than the set point in the solar storage tank or the set point in the auxiliary heater, whichever is higher. Less solar storage capability would be involved in this design, however, because the solar storage tank is prevented from achieving higher temperatures, even when solar energy is available.

In a direct type of solar water heater operating at service pressure, with potable water circulating through the collector, a venting valve is provided near the top of the collector. It would have to be set for release at a pressure several pounds higher than the maximum in the service supply, so the collector storage system must withstand pressure usually above 50 psi. Occasional water loss through venting of steam would be expected.

If a non-pressurized direct type of solar water heater is used, with a float valve in the storage tank, the pressure relief valve can be set to operate at a pressure only slightly above atmospheric. Alternatively, the collector or storage tank may be continuously vented. Oversupply or under-use of solar heated water results in boiling and venting of the storage tank.

PERFORMANCE OF TYPICAL SYSTEMS

GENERAL REQUIREMENTS

A typical family of four persons requires, in the United States, about 80 gallons of hot water per day. At a customary supply temperature of about 140°F, the amount of heat required if the cold inlet is at 60°F is about 50,000 Btu per day.

There is a wide variation in the solar availability from region to region and from season to season in a particular location. There are also the short-term radiation fluctuations due to cloudiness and the day-night cycle.

Seasonal variations in solar availability result in a 200 to 400 percent difference in the solar heat supply to a hot water system. In the winter, for example, an average recovery of 40 percent of 1200 Btu of solar energy per square foot of sloping surface would require approximately 100 square feet of collector for the 50,000 Btu average daily requirement. Such a design would provide essentially all of the hot water needs on an average winter day, but would fall short on days of less than average sunshine. By contrast, a 50-percent recovery of an average summer radiant supply of 2000 Btu per square foot would involve the need for only 50 square feet of collector for satisfying the average hot water requirements.

It is evident that if a 50-square-foot collector were installed, it could supply the major part, perhaps nearly all, of the summer hot water requirements, but it could supply less than half the winter needs. If, on the other hand, a 100-square-foot collector were employed in order that winter needs could be more nearly met, the system would be oversized for summer operation and excess solar heat would have to be wasted. In such circumstances, if an aqueous collection medium were used, boiling of the system would occur and collector or storage venting of steam would have to be provided.

The more important disadvantage of the oversized collector (for summer operation) is the economic penalty associated with investment in a collector which is not fully utilized. Although the cost of the 100-square-foot collector would be approximately double that of the 50-square-foot unit, its annual useful heat delivery would be considerably less than double. It would, of course, deliver about twice as much heat in the winter season, when nearly all of it could be used, but in the other seasons, particularly in summer, heat overflow would occur. The net effect of these factors is a lower economic return, per unit of investment, by the larger system. Stated another way, more Btu per dollar of investment (hence cheaper solar heat) can be delivered by the smaller system.

As a conclusion to the above example, practical design of solar water heaters should be based on desired hot water output in the sunniest months rather than at some other time of year. If based on average daily radiation in the sunniest months, the unit will be slightly oversized and a small amount of heat will be wasted on days of maximum solar input. And quite naturally, on partly cloudy days during the season, some auxiliary heat must be provided. In the month of lowest average solar energy delivery, typically one-half to one-third as much solar heated water can be supplied, or actually the same quantity of water but with a temperature increase above inlet only one-half to one-third as high. Thus, fuel requirements for increasing the temperature of solar heated water to the desired (thermostatted) level could involve one-half to two-thirds of the total energy needed for hot water heating in a mid-winter month.

QUANTITATIVE PERFORMANCE

Although hundreds of thousands of solar water heaters have been used in the United States and abroad, quantitative performance data are extremely limited. In households where no auxiliary heat was used, the solar system probably supplied hot water most of the time, but failed during bad weather. If booster heat was used, hot water was always available, but the relative contributions of solar and auxiliary were seldom measured.

In a few research laboratories, particularly in Australia, some analytical studies of solar water heater performance, confirmed in part by experimental measurements, have been performed. More recently, analytical studies at the University of Wisconsin have been carried out. Table 7-1, based on an Australian study, shows the performance of a double-glazed, 45-square-foot solar water heater in several regions of the country. Variable solar energy and ambient temperature throughout the year result in 1.4 to 2.5 times as much solar heat supply to water in summer than in winter. Climatic differences produced a solar heat percentage ranging from 60 percent to 81 percent of the annual total hot water requirements. Table 7-2 shows monthly performance of the same system, in Melbourne, Australia, with average collection efficiency varying between 29 and 40 percent of incident radiation. Variation in inlet, outlet, and ambient temperature in a typical thermosiphon type of solar water heater is shown in Figure 7-8.

In a simulation study at the University of Wisconsin, hot water usage was programmed for a hypothetical residential user. The results show only slight variation in solar heat utilization at several use schedules and indicate only minor influence of storage temperature stratification on collector efficiency.

Table 7-1

Daily Means for Twelve Consecutive Months of Operation of Solar Water Heaters at Various Localities

Location	Adelaide	Brisbane*	Canberra	Deniliquin	Geelong	Melbourne	Sydney
Hot water discharge ** (gallons, US)	54.2	54.6	51.4	50.9	50.4	54.6	53.9
Electrical energy consumed (kWh)	3.5	2.5	3.4	2.5	3.8	4.6	4.4
Cold water temperature (°C)	17.7	21.6	12.7	16.8	15.9	16.1	16.6
Hot water temperature (°C)	58.9	56.4	58.4	60.3	58.7	57.4	57.7
Energy required to heat water (kWh)	9.8	8.4	10.3	9.7	9.5	9.9	9.8
Heat loss from storage tank (kWh)	2.2	1.9	2.5	2.5	2.2	1.9	1.9
Total energy consumed (kWh)	12.0	10.3	12.8	12.2	11.7	11.8	11.7
Solar energy contributed (kWh)	8.5	7.8	9.4	9.7	7.9	7.2	7.3
Solar energy contributed (%)	71.0	76.0	73.0	81.0	67.0	61.0	62.0
Solar contribution best month (%)	99.0	94.0	98.0	100.0	92.0	95.0	70.0
Solar contribution worst month (%)	47.0	57.0	43.0	57.0	45.0	38.0	51.0
Ratio best to worst	2.1	1.6	2.3	1.8	2.0	2.5	1.4

* Hail screens suspended above the absorbers. No correction made for reduction of absorbing area.

** Water discharged at 6:00 a.m. daily

Double-glazed, flat-black, 45 square foot solar collector tilted toward equator at latitude angle plus 2.5 degrees. Storage 84 gallons (US). Thermosiphon circulation. Electric auxiliary heat.

Table 7-2

Solar Water Heater Performance in Melbourne, Australia

Month	Mean Insolation on Absorber	Mean Daily Supplementary Energy	Mean Daily Solar Energy Contribution		System Efficiency
	Btu/ft^2 day	kWh	Percent	kWh	Percent
January	1630	2.9	75	8.9	40
February	2220	0.5	95	9.5	32
March	1690	2.6	74	7.4	33
April	1240	5.2	52	5.6	34
May	1290	6.2	47	5.5	32
June	1220	7.7	39	4.9	30
July	1290	8.1	38	5.0	29
August	1530	6.1	50	6.1	30
September	1600	4.9	59	7.1	33
October	1860	3.9	67	7.9	32
November	1880	3.7	68	7.9	32
December	1790	3.5	72	9.0	38
Year	1610	4.6	61	7.2	35

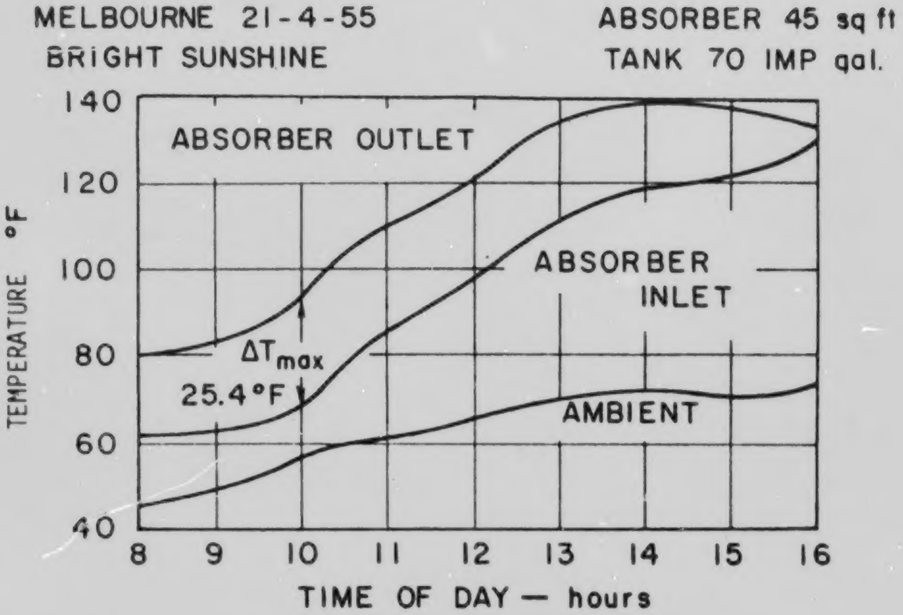


Figure 7-8. Absorber and Tank Temperatures for Thermosiphon Flow During a Typical Day

In summary, the normal output of well-designed solar water heating systems can be roughly estimated by assuming approximately 40 percent solar collection efficiency. Average monthly solar radiation multiplied by collector area and 40 percent delivery efficiency can provide a rough measure of daily or monthly Btu delivery. The total Btu requirements for the hot water supply, based on the volume used and the temperature increase set, then serve the basis for computation of percentage contribution from solar and the portion required to be supplied by fuel or electricity.

Sizing the Collectors

The curves shown in Figure 7-9 may be used to estimate the solar collector size required for hot water service in residential buildings having typical hot water systems. The system is assumed to be pumped liquid type, with liquid-to-liquid heat exchange, delivering hot water to scheduled residential uses from 6:00 a.m. until midnight. The shaded band represents results of computer calculations for eleven different locations in the United States. The cities included in the study are Boulder, Colorado; Albuquerque, New Mexico; Madison, Wisconsin; Boston, Massachusetts; Oak Ridge, Tennessee; Albany, New York; Manhattan, Kansas; Gainesville, Florida; Santa Maria, California; St. Cloud, Minnesota; and Washington, D.C. The separate curve above the shaded band is the result for Seattle, Washington, and is distinctly different from other areas of the country. The hot water loads used in the computations range from 50 gallons per day (gpd) to 2000 gpd. The sizing curves are approximate and should not be expected to yield results closer than 10 percent of actual value.

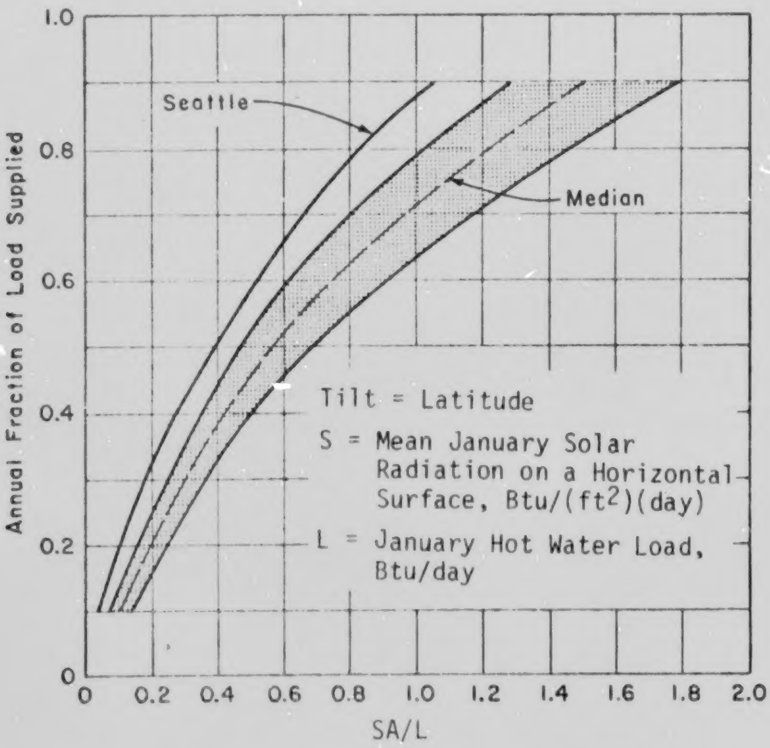


Figure 7-9. Fraction of Annual Load Supplied by Solar as a Function of January Conditions for Hot Water Heaters

The vertical axis shows the fraction of the annual water heating load supplied by solar. The horizontal axis shows values of the parameters, SA/L , which involves the average daily January radiation on a horizontal surface, S ; the required collector area, A, to supply a certain percentage of the daily hot water load, L. The January average daily total radiation at locations in the United States can be estimated from the radiation map in Figure 7-10. Values on the map are given in Btu/(ft^2)(day). The curves are not applicable for values of f greater than 0.9.

It should be remembered that the service hot water load will be nearly constant throughout the year while the solar energy collected will vary from season to season. A system sized for January, with collectors tilted at the latitude angle, will deliver high temperature water and may even cause boiling in the summer. On the other hand, a system sized to meet the load in July will not provide all of the load in the winter months. Orientation of the collector can partially overcome month-to-month fluctuations in radiation and temperature.

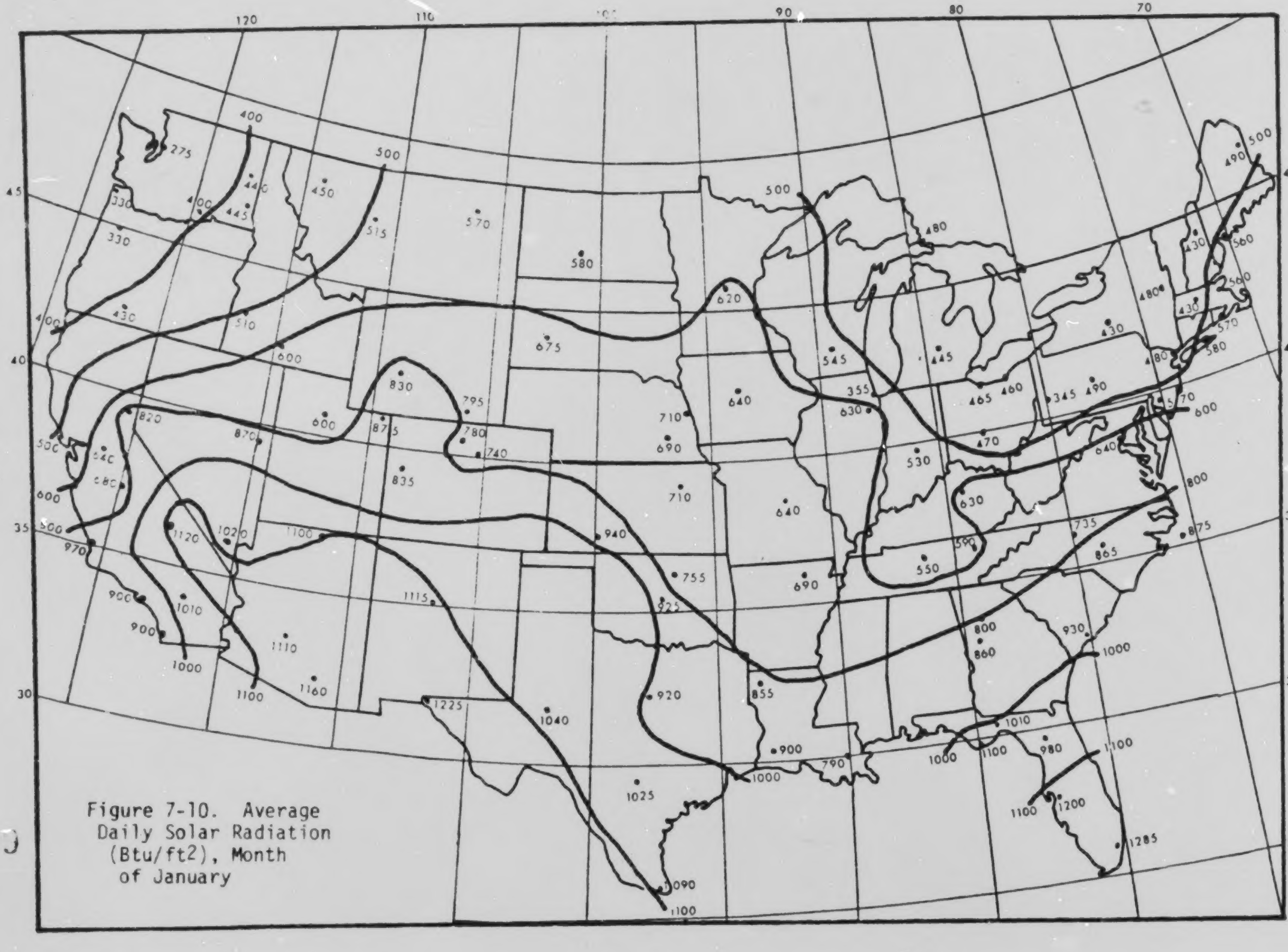
Sizing Examples

Example 7-1. Determine the approximate size of collector needed to provide hot water for a family of four in a residential building in Kansas City, Missouri.

Solution: The average daily service hot water load in January is:

$$L = 80 \text{ gallons/day} \times 8.34 \text{ pounds/gallon} \times 1 \text{ Btu/(lb)(°F)} \times (140°F - 50°F) = 60{,}048 \text{ Btu/day}$$

The desired service water temperature is 140°F and the temperature of the cold water from the main is 50°F. The total average solar radiation, S,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460
345
490
480
570
600
500
640
820
870
680
600
500
970
1120
1020
1100
940
710
640
530
470
640
630
800
590
550
735
865
875
755
690
925
1115
900
1010
900
1000
1110
1100
1160
1225
1040
920
855
800
860
930
1000
1010
980
1100
1000
1100
900
790
1000
1025
1100
1200
1285
1090
1100

Figure 7-10. Average Daily Solar Radiation (Btu/ft2), Month of January

available in January, from Figure 7-10, is 680 Btu per square foot per day. For a water system to provide 60 percent of the annual load, from Figure 7-9, SA/L is about 0.8. Therefore:

$$A = 0.8 \times L/S = (0.8 \times 60048)/680 = 70.6 \text{ square feet.}$$

If 3-by-8-foot collector modules are available, 2.9 units would be required. Three collector units should therefore be used.

Example 7-2. Determine the size of collector needed to provide hot water for a family of four in Albuquerque, New Mexico.

Solution: The monthly load will be approximately the same as in Example 7-1:

$$L = 60{,}048 \text{ Btu/day}$$

From Figure 7-10, $S = 1115$ Btu/(ft^2)(day). For a system to provide 60 percent of the annual load, Figure 7-9 shows that SA/L is approximately 0.8. The collector area required is:

$$A = (0.8 \times 60048)/1115 = 43.1$$

Using 3 by 6 foot collector modules, 2.4 units would be required for this system; either two or three modules should be used. If two modules are used, the system would be expected to provide less than 60 percent of the annual load.

COSTS

The cost of installing a solar water heater (exclusive of the hardware) may range from about \$300 for a system with a roof-mounted collector to over \$1000 for a collector mounted on a stand adjacent to a house. In a recent procurement of several types of solar water heaters for ground mounting next to existing houses, an electric utility company spent \$1500 to \$2000 for each system, including hardware, and totally installed.

Non-freezing collectors of about 50 square feet, 80 gallon water tanks, pumps, fans, and controls were included.

A solar collector manufacturer has announced the availability of a solar water heater "package" having a retail price of $995. The package consists of a 40 square foot drainable collector, an 80 gallon storage tank, pumps, and controls. Installation and hook-up to the conventional system are not included.

As designs are standardized and manufacturing volume increases, it may be anticipated that the total installed cost of an average-sized residential solar water heating system will be less than $1000. Assuming a collector area of about 50 square feet and a reasonably sunny climate, this unit should be able to deliver at least 250,000 Btu per square foot of collector per year, for a total of 12.5 million Btu annually. With an average daily requirement for 50,000 Btu of heat for hot water, the 18 million Btu annually required could be two-thirds solar. If electric heat at five cents per kilowatt-hour (about $14 per million Btu) is being replaced, an annual electric saving of about $175 is achieved. A $1000 solar water heater could thus pay for itself from electric savings in about six years. Or, if conventionally financed at 8-percent interest, an annual cost of interest plus principal of, say, 12 percent, or $120 per year, would be less than the electric savings by something over $50 per year. This favorable economic comparison for solar water heaters is applicable now in many parts of the country and should prevail very generally in the next few years.

TRAINING COURSE IN
THE PRACTICAL ASPECTS OF
SIZING, INSTALLATION, AND OPERATION OF SOLAR HEATING AND COOLING SYSTEMS
FOR
RESIDENTIAL BUILDINGS

MODULE 8

SOLAR HEATING SYSTEMS

SOLAR ENERGY APPLICATIONS LABORATORY
COLORADO STATE UNIVERSITY
FORT COLLINS, COLORADO

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INTRODUCTION

Solar heat from the collectors and the heating demand for a building are not usually in balance. Consequently, mechanical equipment is required for proper comfort control. The central component of the solar system is the heat storage unit. The heat storage unit receives heat from the collectors when the solar heat exceeds the heating load and delivers heat to the rooms when the heating load exceeds the solar heat available from the collectors. When solar heat has been depleted from storage, the auxiliary boiler or furnace supplies the heat to meet the heating load. The system should be easy to operate, require little maintenance, and provide the comfort level demanded by the occupants in the building.

OBJECTIVE

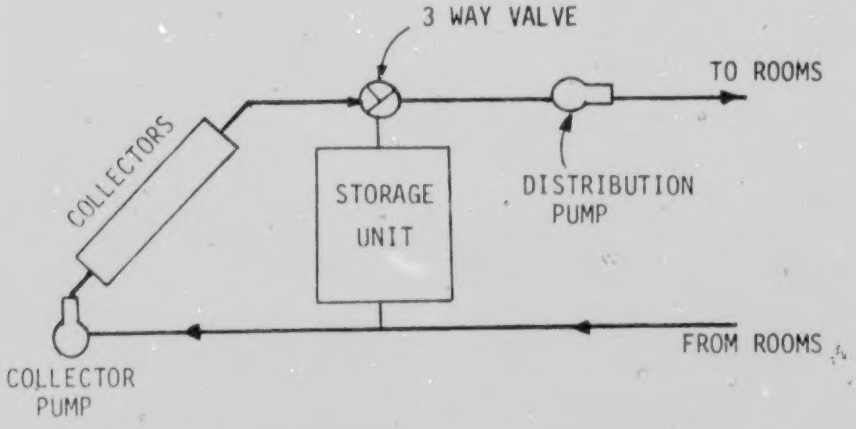
The objective of the trainee is to be able to choose, install, operate, and maintain a solar space heating system. At the end of this module the trainee should be able to:

1. Differentiate between air and liquid systems,
2. Select and specify the components of a solar heating system,
3. Discuss the use of an auxiliary energy source,
4. Describe the different modes of operation of a solar space heating system.

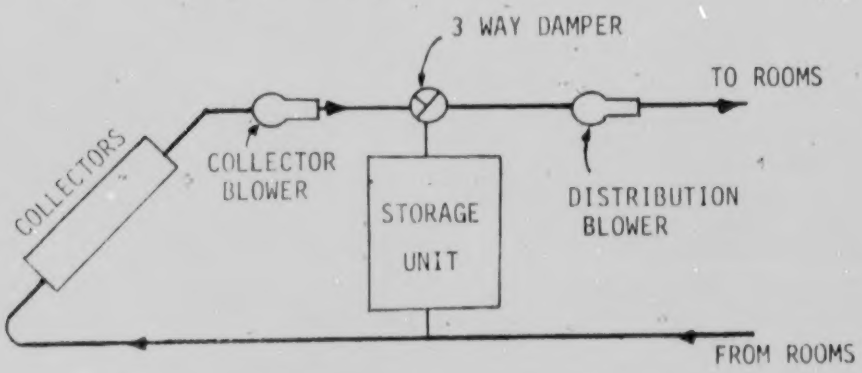
SOLAR SPACE HEATING SYSTEMS

The basic arrangement to accomplish solar space heating is shown in Figure 8-1(a) for a liquid system, and 8-1(b) for an air system. By positioning the three-way dampers (or valves) and controlling the blowers (or pumps) on or off, three "modes" of operation are possible:

1. Heating the building directly from the collectors
2. Heating the storage unit from the collectors
3. Heating the building from the storage unit.


3 WAY VALVE
TO ROOMS
COLLECTORS
STORAGE UNIT
DISTRIBUTION PUMP
FROM ROOMS
COLLECTOR PUMP

(a) Liquid System


3 WAY DAMPER
TO ROOMS
COLLECTORS
COLLECTOR BLOWER
STORAGE UNIT
DISTRIBUTION BLOWER
FROM ROOMS

(b) Air System

Figure 8-1. Basic Arrangements for Solar Space Heating Systems

In a water system the collection and distribution circuits may each be connected to the water storage tank and the three-way valves may be eliminated (Figure 8-2). The three modes are obtained by on and off control of the two pumps.

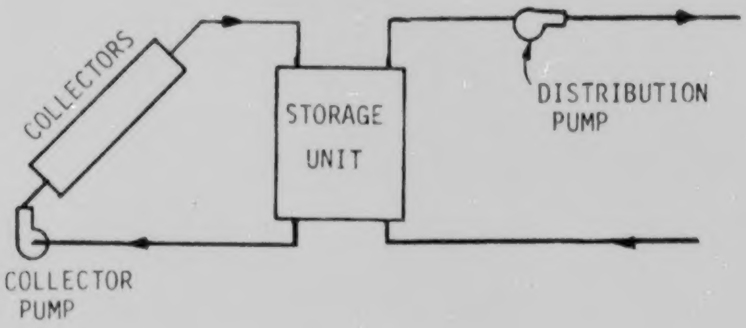

COLLECTORS
STORAGE UNIT
DISTRIBUTION PUMP
COLLECTOR PUMP

Figure 8-2. Water System Arrangement for Solar Space Heating

Since there are periods when neither the collectors nor the storage unit can meet the demand for heat, an auxiliary heater (fuel or electric) having the capacity to carry the maximum heating load is required. Solar and auxiliary heat may be supplied to the building by the same heat distribution system. The air heating solar system may use a conventional warm-air furnace directly in the hot air supply duct, as shown in Figure 8-3. Fuel is supplied to the auxiliary unit only when solar heat is insufficient to maintain the desired room temperature.

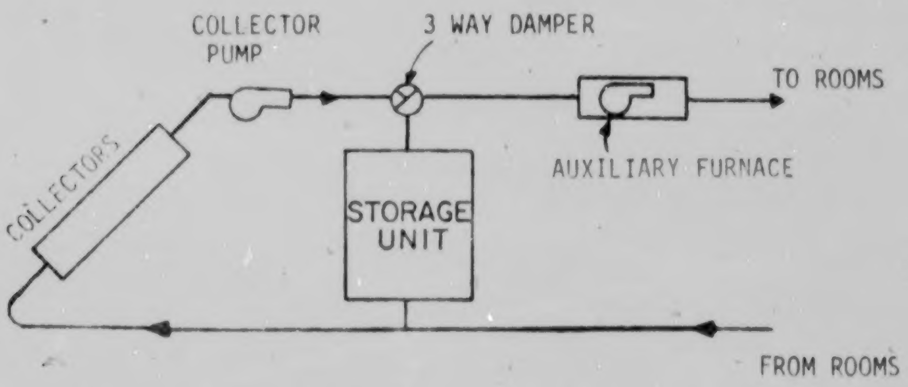

COLLECTOR PUMP
3 WAY DAMPER
TO ROOMS
AUXILIARY FURNACE
COLLECTORS
STORAGE UNIT
FROM ROOMS

Figure 8-3. Air System for Solar Space Heating with Auxiliary Furnace

In the liquid system a hot water boiler (fuel or electric) is used, preferably locating the boiler in a by-pass circuit as shown in Figure 8-4. The boiler by-pass is used to prevent heating the storage with auxiliary energy. Heat from the auxiliary boiler should not be supplied to the storage tank because it is wasteful use of energy.

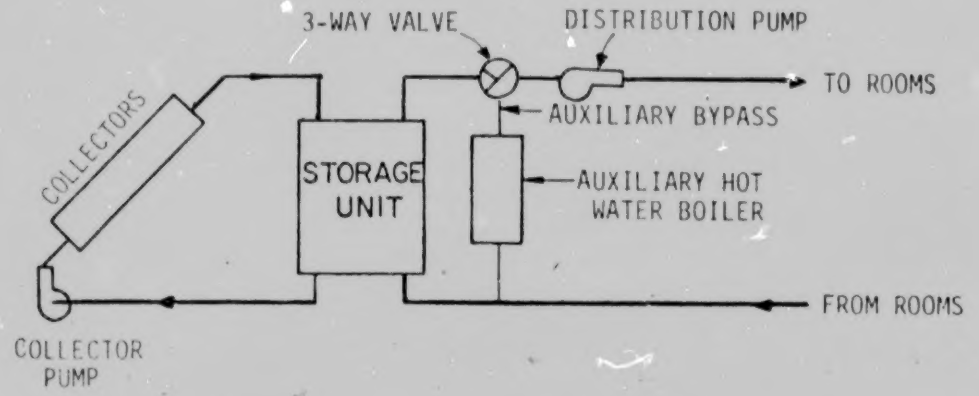

3-WAY VALVE
DISTRIBUTION PUMP
TO ROOMS
AUXILIARY BYPASS
COLLECTORS
STORAGE UNIT
AUXILIARY HOT WATER BOILER
FROM ROOMS
COLLECTOR PUMP

Figure 8-4. Liquid System for Solar Space Heating with Auxiliary Boiler

SOLAR AIR HEATING SYSTEM

Double Blower Design

The schematic design of a two-blower air-type solar system shown in Figure 8-3 comprises four principal components; solar collector, heat storage unit, air handler, and auxiliary heater. By combining the blower and dampers in an "air handler", installation and operation of the system can be simplified. The operation of such a system in its several modes is listed in Table 8-1 and shown in Figures 8-5, 8-6, and 8-7. In the table and figures, MD denotes motorized damper and BD a back draft damper.

Table 8-1. Two-Blower, Air-Type Solar System Operation

Mode	MD 1	MD 2	BD 1	BD 2	Collector Blower	Distribution Blower
Room Heating from Collector (Figure 8-5)	Open	Open	Open	Open	On	On
Heating Storage (Figure 8-6)	Open	Closed	Open	Closed	On	Off
Room Heating from Storage (Figure 8-7)	Closed	Open	Closed	Open	Off	On
Heating from Auxiliary (Figure 8-7)	Closed	Open	Closed (auxiliary on)	Open	Off	On

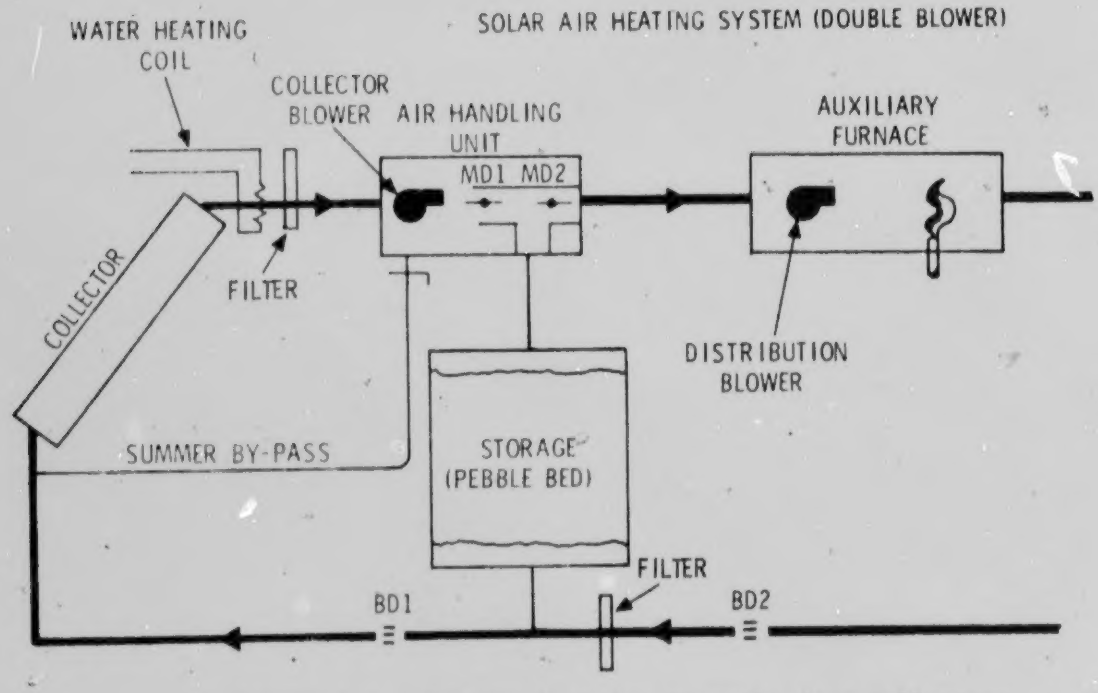

SOLAR AIR HEATING SYSTEM (DOUBLE BLOWER)
WATER HEATING COIL
COLLECTOR BLOWER
AIR HANDLING UNIT
MD1
MD2
AUXILIARY FURNACE
COLLECTOR
FILTER
DISTRIBUTION BLOWER
STORAGE (PEBBLE BED)
SUMMER BY-PASS
FILTER
BD1
BD2

Figure 8-5. Heating Building Directly from Collectors

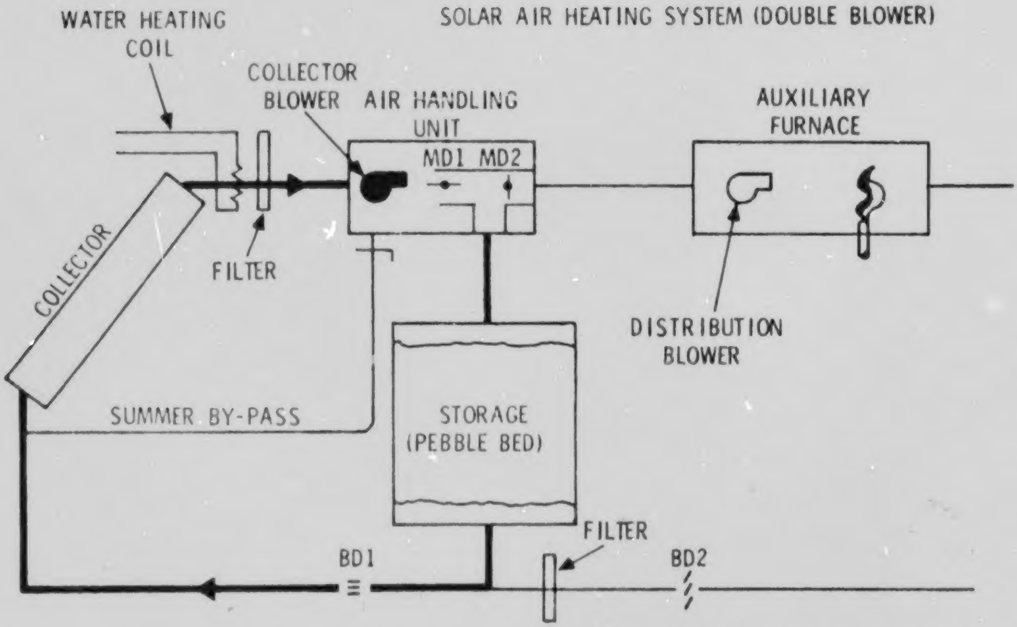

SOLAR AIR HEATING SYSTEM (DOUBLE BLOWER)
WATER HEATING COIL
COLLECTOR BLOWER
AIR HANDLING UNIT
MD1 MD2
AUXILIARY FURNACE
COLLECTOR
FILTER
DISTRIBUTION BLOWER
SUMMER BY-PASS
STORAGE (PEBBLE BED)
FILTER
BD1
BD2

Figure 8-6. Storing Heat from Collectors

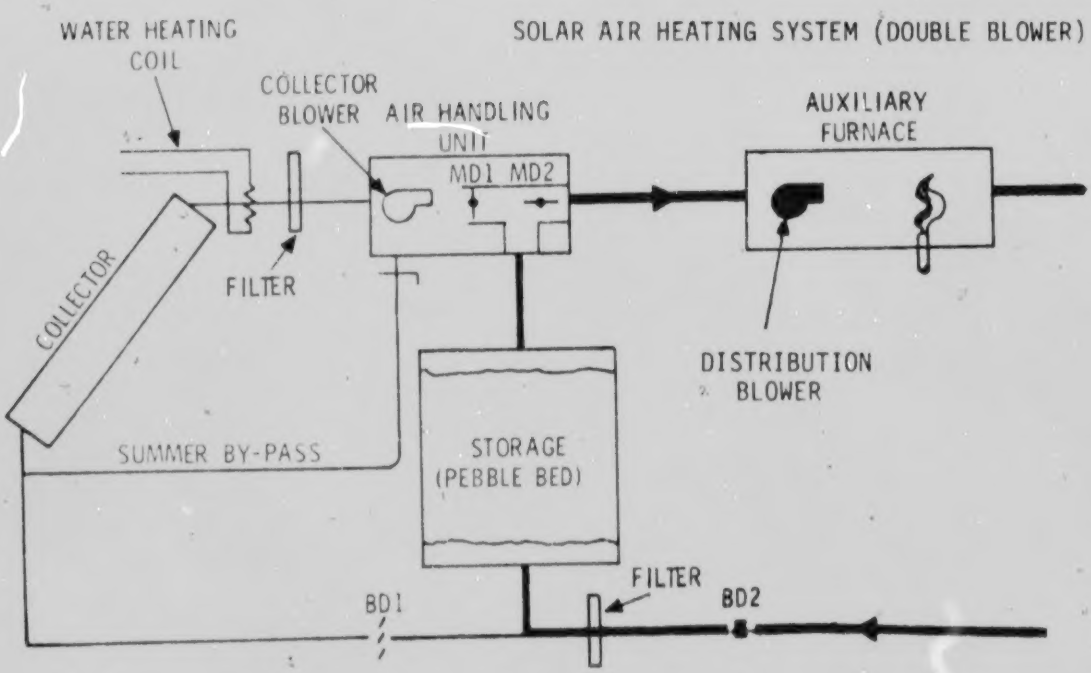

WATER HEATING COIL
SOLAR AIR HEATING SYSTEM (DOUBLE BLOWER)
COLLECTOR BLOWER
AIR HANDLING UNIT
MD1 MD2
AUXILIARY FURNACE
COLLECTOR
FILTER
DISTRIBUTION BLOWER
SUMMER BY-PASS
STORAGE (PEBBLE BED)
FILTER
BD1
BD2

Figure 8-7. Heating Building from Storage Unit
(Also Heating from Auxiliary)

So that the domestic hot water supply can be solar heated in the summer when no space heating is needed, the heat storage unit and heated space can be by-passed as shown in Figure 8-8. A manual damper is opened in the by-pass duct so that air is circulated in a closed loop between collector, water heating coil, and the collector blower. Damper MD 1 in the closed position prevents flow of hot air to storage or the rooms.

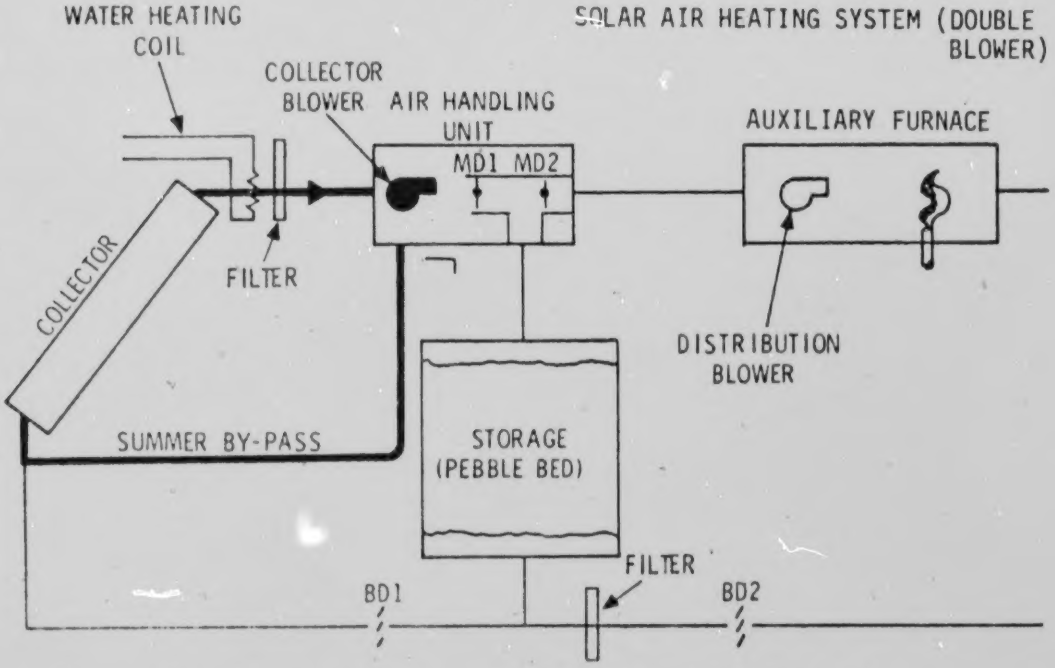

WATER HEATING COIL
SOLAR AIR HEATING SYSTEM (DOUBLE BLOWER)
COLLECTOR BLOWER
AIR HANDLING UNIT
MD1 MD2
AUXILIARY FURNACE
COLLECTOR
FILTER
DISTRIBUTION BLOWER
SUMMER BY-PASS
STORAGE (PEBBLE BED)
FILTER
BD1
BD2

Figure 8-8. Service Hot Water Heating (Summer Operation)

Most commercially available warm-air furnaces for residential use contain a blower for circulation of warm air through the building via the distribution ducts. In a typical all-air solar installation, the furnace blower is used in the normal manner for distributing warm air, supplied either from the collectors or from storage. The solar system blower operates only when air is circulated through the collector.

Single Blower Design

Another damper arrangement does not require the furnace blower, so only the solar system blower is needed. Four motorized dampers are required (rather than two), but only two actuators are needed. This system type is shown in Figure 8-9, with the blower and motorized dampers in an "air handler" cabinet. Although the cost of a blower and motor can be saved by this design, two additional dampers are required, the controls are more complicated, air flow rates in the several modes are less adjustable, and the "saved" blower and motor are usually integral parts of the auxiliary furnace.

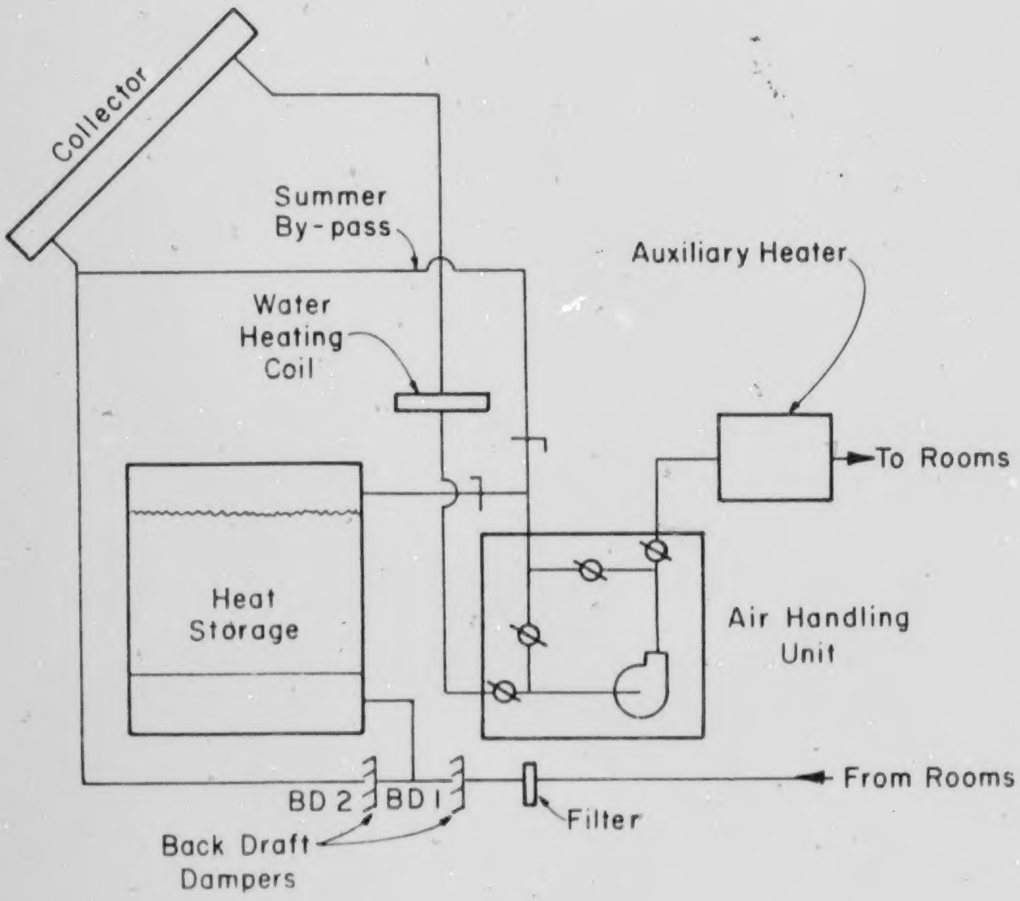

Collector
Summer By-pass
Auxiliary Heater
Water Heating Coil
To Rooms
Heat Storage
Air Handling Unit
From Rooms
BD 2
BD 1
Filter
Back Draft Dampers

Figure 8-9. Single Blower System

Solar Air System Materials, Components, and Installation

Important operating considerations in the air type system are blower power requirements and air leakage. A well-designed air system has approximately equal pressure loss through the collectors and pebble-bed, typically about 0.3 inch water gauge in each unit. With ducting and filters, the total system pressure can approach one inch of water. The total pressure in an air type solar system is about twice that usually encountered in a conventional forced air distribution system, so additional blower power is required. Typical requirement in a conventional system is one-half to three-fourths horsepower for a 1500 cfm system. The blowers also operate for longer periods than in the conventional system because of their use both for solar heat collection and for heat distribution. A one-inch water gauge pressure loss is about the maximum acceptable from the standpoint of blower power cost.

Leakage of air in ducts, collectors, and storage is of greater concern in a solar heating system than in a conventional system because the pressure is higher, there is more ducting, the system operates for longer periods, and there may be more ducting through unheated space. The ducts should therefore be made with taped or sealed joints and tightly fitted dampers. The ducts may be of fiberglass board or insulated sheet metal. Insulation is needed to reduce heat loss through the duct walls, particularly in unheated spaces such as attics. At least one inch of fiberglass with a rating of R-4 is recommended for duct insulation.

It is especially important with a solar air system that a well scheduled installation be made. More space and access must be provided in the building for ducting than for pipes in a liquid system. Ductwork and component assembly can be done at the same time that the distribution ducts and furnace are installed in a typical construction schedule.

There must be provision for construction and installation space and for full access to the space for systems and components.

If fiberglass ductboard is used for the air duct, it should not be in locations where it can be damaged by moving objects or occupants. Joints should be well sealed with tapes or mastics recommended by the industry. Duct bends should be provided with turning vanes to reduce losses. Ducts should be sized for air velocities between 700 and 1000 feet per minute.

Blowers, dampers, and auxiliary heaters may be provided by a single solar system supplier or they may be purchased separately. If separately purchased, blowers should be forward-curved squirrel cage type and belt-driven at 900 to 1700 rpm. Direct coupled blowers with motors in the air stream may have shorter service life because of motor operation in high-temperature air. Flexible connections between blowers and ducts are recommended.

Louver-type dampers with live silicon rubber seals are recommended for positive shut off and smooth stroking. Damper drive motors should be located on the outside of ducts and direct coupled to the damper shaft or through linkages. Damper pairs may be operated by the same drive motor such that one is closed when the other is open. Damper motors are available which operate on low voltage (24 volt) and have spring returns.

Back draft dampers, used in ducts to prevent reverse flow, may be of the flexible flat type or shutter type. They must be mounted to provide a positive seal against reverse air flow.

To prevent fouling and increased pressure loss in the pebble-bed, filters should be installed in the air streams entering both ends of the storage unit. The filters should be changed or cleaned every few weeks during the first several months of operation to remove the initial dust in the system and building.

Provision for supply of domestic hot water can be easily made in the air system by the use of an air-to-water heat exchanger in the hot air duct between the collector and blower. The heat exchanger coil is a finned type, with one or two rows of tubes. A small pump circulates water from the bottom of an insulated tank (usually about 80-gallon capacity), through the coil, and back to the top of the tank. The cold water enters the solar-heated tank and warm water flows to a conventional automatic water heater whenever a hot water faucet is opened in the building. A duct by-pass as shown in Figure 8-7 (page 8-6) permits operation of the service hot water coil in the summer without heating the pebble-bed. A thermostatic mixing valve can be installed in the line connected to the service hot water tank from the cold water main to prevent delivery of scalding hot water.

The complete solar heating installation will require heating and sheet metal workers to install collectors, ducts, dampers, and the conventional system, electricians to wire blowers and dampers, plumbers to connect the domestic water heating system, and carpenters or masonry workers to construct the pebble-bed container. Consequently, the general contractor and the solar system contractor should coordinate their activities so that each task is accomplished at the most appropriate and convenient stage during construction. Quality installation is an important requirement to obtain a high performance air heating solar system.

LIQUID HEATING SOLAR SYSTEM

A schematic diagram of a complete liquid-heating solar system for solar space heating using water as the heat transport and storage fluid is shown in Figure 8-10. The system is comprised of solar collectors, storage tank, auxiliary boiler, and pumps, valves, and heat exchangers.

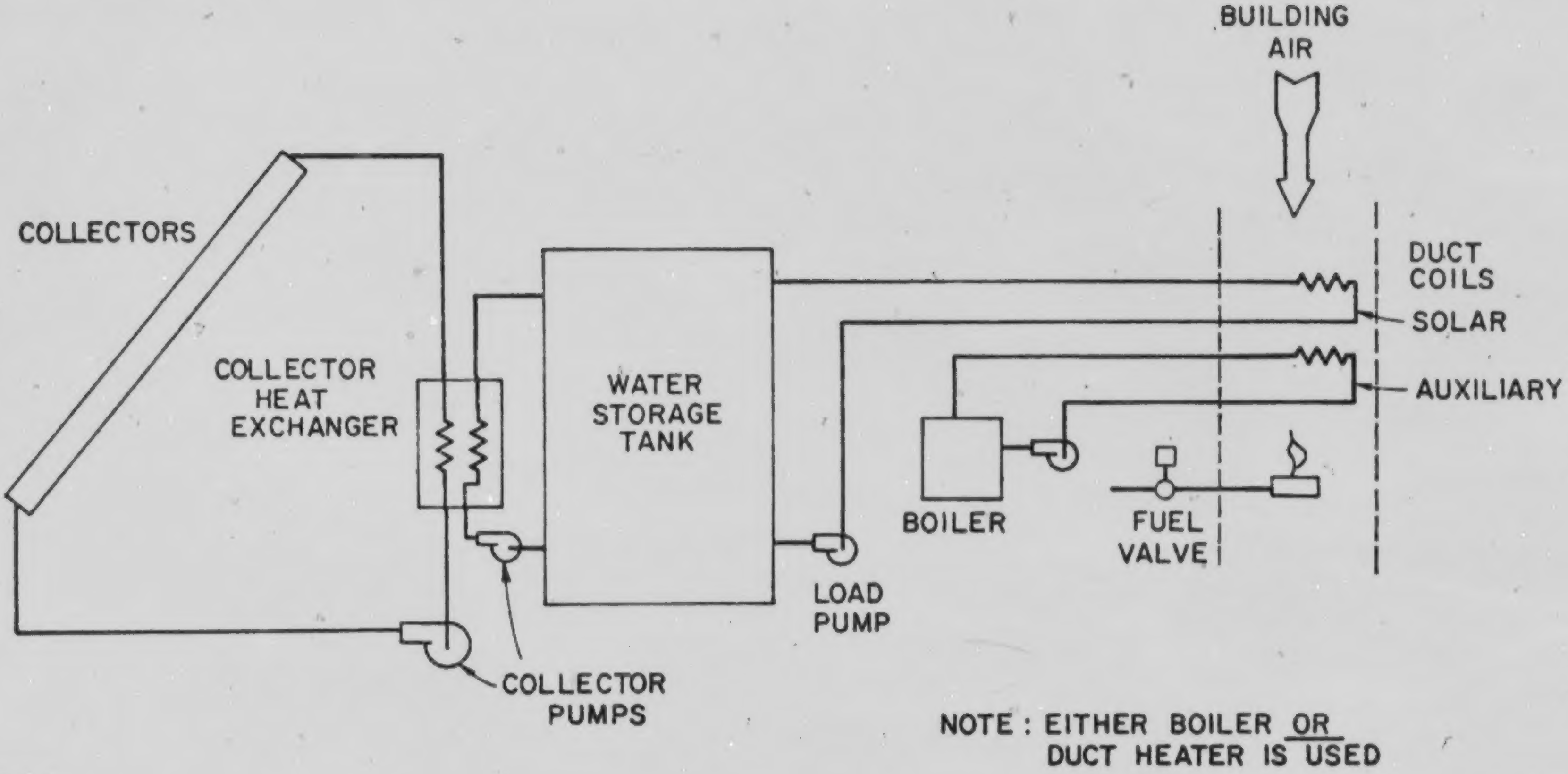

BUILDING AIR
COLLECTORS
DUCT COILS
SOLAR
COLLECTOR HEAT EXCHANGER
WATER STORAGE TANK
AUXILIARY
BOILER
FUEL VALVE
LOAD PUMP
COLLECTOR PUMPS
NOTE: EITHER BOILER OR DUCT HEATER IS USED

Figure 8-10. Water Type Solar Space Heating System

The collector heat exchanger is used for systems in freezing climates to separate the antifreeze in the collector loop from the storage tank water. The heat exchanger may be a counterflow tube-in-shell type.

A central heat distribution system with a single heat exchanger coil or multiple fan coil units in different zones in the building may be used to heat the rooms. Radiant or baseboard convection heating is an alternative method for heat delivery but for satisfactory performance, higher temperatures are required than for forced air heat exchangers. The higher temperature is a disadvantage to system operation with flat-plate collectors. The auxiliary heater may be either a boiler or an air duct furnace.

The operating modes and states of the pumps, blower, and auxiliary heater are shown in Table 8-2. The locations of the components are shown on Figure 8-10.

Table 8-2. Conditions of Pumps and Valves for Solar Water Heating Systems

Mode	Collector Pumps	Load Pump	Auxiliary Heater	Distribution Blower
Heating Storage	on	—	—	—
Heating from Storage	—	on	off	on
Heating from Auxiliary	—	on or off	on	on

Solar Water System Materials, Components, and Installation

Piping may consist of either copper or high temperature (CPVC) plastic pipe and all pipes should be insulated with appropriate material such as neoprene foam at least one-half inch in thickness. Care should be taken to allow thermal expansion of the pipes, and long pipe lengths should provide more freedom for expansion than short lengths. Pipes should be sized so that water velocity does not exceed five feet per second.

In Table 8-3, recommended pipe diameters are indicated for flow rates in gallons per minute.

Table 8-3. Recommended Pipe Diameters for Various Flow Rates

Select Pipe Size	Gallons per Minute	Velocity FPS	Pressure Drop per 100 feet PSI
3/8	2	3.36	6.58
1/2	4	4.22	7.42
3/4	8	4.81	6.60
1	15	5.57	6.36
1-1/4	25	5.37	4.22

Circulating pumps should be centrifugal type, coupled directly to motors with rotating speeds between 700 and 1700 rpm. Centrifugal pumps are recommended because the pumping pressure is limited and if valves fail to open, or the pipeline becomes clogged, there is no danger of developing excessive pressures which could burst pipes. With known flow rate and system head, pumps may be selected from stock items in catalogs, or made to specifications by pump manufacturers. Impellers of stock item pumps may be trimmed to meet the specifications. Centrifugal pumps should be located so that priming is not necessary, which could be a particular problem in a vented system or where a storage tank is underground. The pumps should be provided with at least five feet of head on the suction side.

HEAT EXCHANGERS

A heat exchanger must be provided to transfer the heat from the collector fluid to storage if the collector and storage fluids are in different loops. Because of the low temperatures from flat-plate solar collectors, the temperature difference across heat exchangers should be small. The temperature differential in a heat exchanger is minimized in two ways: by providing a large surface area for heat transfer in the exchanger and by maintaining high flow rates through the exchanger. Tube-in-shell heat exchangers are simple, efficient, and readily available. They consist of single or multiple tubes enclosed within an outer jacket. One fluid passes through the tubes while the other fluid passes outside the tubes. Large heat transfer surface can be achieved in compact arrangements.

The performance characteristics of a single-pass counterflow heat exchanger are illustrated in Figure 8-11. It can be seen from the temperature profiles along the exchanger that the temperature difference between fluids is reasonably small along the length of the heat exchanger.

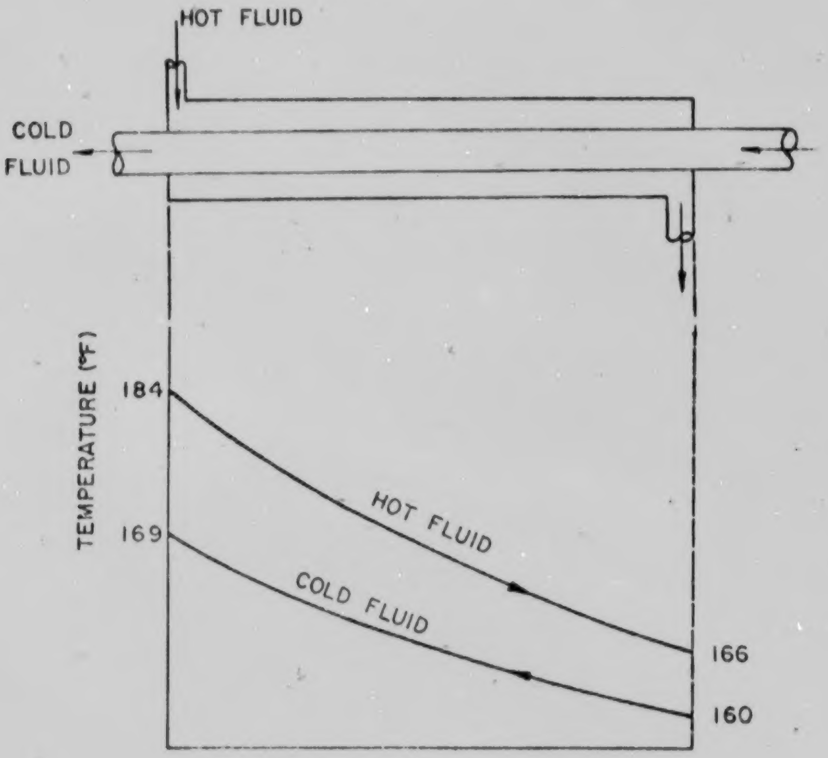


Figure 8-11. Single-Pass Counterflow Heat Exchanger (Collector Heat Exchanger at 115,500 Btu/Hr and Storage Temperature of 160°F)

The manufacturer's guide can easily be followed in selecting the size of a heat exchanger. If appropriate information is difficult to acquire, the manufacturer's representative should be consulted for assistance and/or advice. The information necessary for heat exchanger sizing and fluid flow rate determination are the temperature of the fluids entering the exchanger and the Btu per hour heat transfer rate desired.

High fluid velocities and flow rates achieve high heat exchanger efficiency at the expense of pumping power. The high flow rate, however, minimizes thermal stratification in the storage tank because of mixing. However, achieving efficiency in heat exchange from the collectors to storage and from storage to the loads is more important to overall system performance than establishing stratification in the storage tank.

AUXILIARY HEATING UNIT

The auxiliary heating unit may be a hot water boiler, forced air furnace, or electric heat pump. If a hot water boiler is used, water may be distributed to individual room heating units. This allows the same heat distribution line to be used for solar and auxiliary heated water. It is advisable to install the auxiliary boiler in a by-pass line around the storage unit as shown in Figure 8-4 (page 8-4). This arrangement prevents heating water in storage with auxiliary energy. Because the boiler is used only occasionally in the solar system, it is preferable to operate a cold boiler, which maintains low temperature until auxiliary heat is required. This prevents heat loss to the boiler flue and also heat load to the building from a high temperature boiler.

AIR HEATING COILS

The room air may be heated by finned duct coils in a central air distribution system, fan coil units in different zones in the building, or by baseboard radiant heating units. The temperature of the heated water used in each type of heating unit is important. Radiant heating systems require higher water temperatures than duct or fan coil systems to heat the rooms effectively.

The temperature in a solar storage tank which is heated by flat-plate solar collectors will range between 100° and 160°F in the winter. Baseboard or radiant heating equipment is normally designed for water temperatures at 180° to 220°F. Therefore, the baseboard or radiant heating systems are not recommended for use in heating a building with a solar system which incorporates flat-plate collectors.

Because of space limitations or other reasons, fan coil units may be preferred over duct coils to heat room air. The units should be sized to provide a required rate of heating with water temperature of about 140°F. Duct heating coils may be used with a central forced air system. These units are commercially available and consist of multiple rows of finned tubes. Air velocity across these coils should be at least 500 feet per minute. Manufacturers of heating units will provide the proper size for given water temperatures and design heat rate requirements of the unit. Separate duct heating coils for solar heated water and for auxiliary boiler heated water may be considered in a central air distribution system. Two separate coils will permit heat to be extracted from storage until the water temperature is practically at room temperature, while the auxiliary heat will be used as necessary to deliver the rate of heat required to maintain the comfort conditions in the rooms. This arrangement necessitates a second pump, air heating coil, and additional piping connections. If two coils are used, the solar heated coil should be the first coil in the direction of air flow, followed by the auxiliary coil. If a duct furnace is used for auxiliary heating, the solar air heating coil should be installed ahead of the furnace or at the return air connection to the furnace. The solar coil will then heat the coldest air.

In a solar system, a single pump may be used to circulate water through two different circuits. For example, the solar heated water is directed to a heating coil in winter and to an air conditioning unit in summer. Switching the fluid circuits is accomplished by a three-way valve. Various types of three-way valves are available and are suitable for use. However, if there is a leak through the valve, the system performance can be affected adversely, so that properly seating valves should be selected and tested early during the start-up operations.

HEAT PUMPS

A heat pump uses electrical or chemical energy to extract heat from a low temperature source and deliver the heat to a higher temperature sink. The process is identical to a refrigeration cycle and the same machine that is used as a heat pump in winter may be used as a refrigeration air conditioner in summer. The switching between heating and cooling may be done internally to the machine by reversing the evaporator and condenser units, or externally by reversing the exchange circuits on the evaporator and condenser side of the machine.

Heat pumps are classified according to the heat source and the fluid to which heat is delivered. There are three types of heat pumps: (1) air-to-air, (2) water-to-air, and (3) water-to-water. Schematic diagrams of a heat pump operating as a heater and as a cooler are shown in Figures 8-12 and 8-13, respectively.

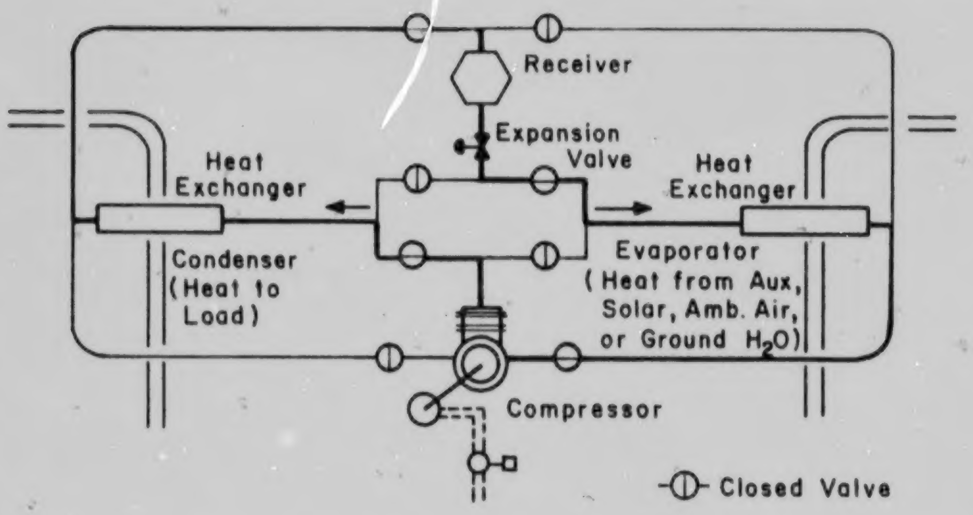

Receiver
Expansion Valve
Heat Exchanger
Heat Exchanger
Condenser (Heat to Load)
Evaporator (Heat from Aux, Solar, Amb. Air, or Ground H_2O)
Compressor
Closed Valve
Open Valve

Figure 8-12. Heat Pump in Heating Mode

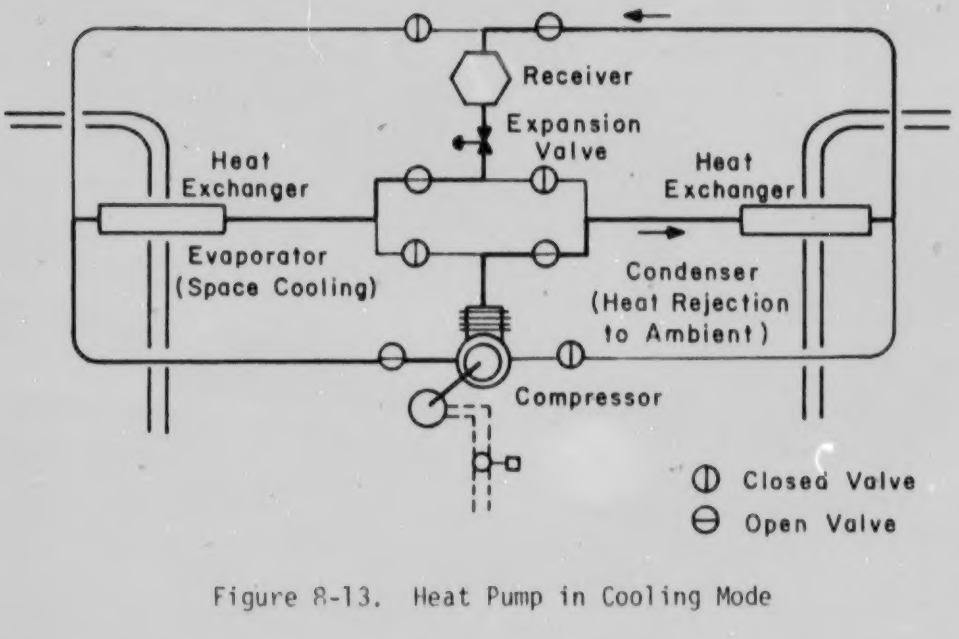

Receiver
Expansion Valve
Heat Exchanger
Heat Exchanger
Evaporator (Space Cooling)
Condenser (Heat Rejection to Ambient)
Compressor
Closed Valve
Open Valve

Figure 8-13. Heat Pump in Cooling Mode

SOLAR ASSISTED HEAT PUMPS

The concept of a solar-assisted heat pump is to supply a higher temperature heat source than outdoor ambient air to the heat pump from solar collectors or storage. Typically, solar heated air or water could be 40° to 110°F above the ambient air or water temperature. Because the fluid temperature delivered from the collectors is low, greater efficiency is expected from the solar system as compared to a solar system using direct heating methods, which typically requires 150°F water temperatures above ambient. A solar heat pump system is appropriate in extremely cold, windy, or cloudy areas where flat-plate collectors could be used effectively to collect solar energy at temperatures sufficient for a heat pump.

Heat is usually stored for the low temperature side of the heat pump because it results in better system efficiency and smaller size unit than if storage is provided in the "hot side". A possible system is illustrated in Figure 8-14. Solar air heating collectors with a pebble-bed storage unit or liquid heating collectors with water or phase change storage may be used along with any of the three types of heat pumps available commercially.

There is not yet a clear indication of what heat pump arrangement is going to prove best. With an air system, it appears that the heat pump can be most advantageously used if operated simply as the auxiliary furnace to raise the temperature of the circulating air from the pebble-bed to the rooms. The system is illustrated in Figure 8-15, where outdoor air is used as the source. In the liquid system,whether the heat pump should be used in a similar fashion, or whether the source should be the solar storage tank, is not yet clear. At this time, an engineer and the heat pump manufacturer should be consulted to assist in the design of a solar heat pump combination.

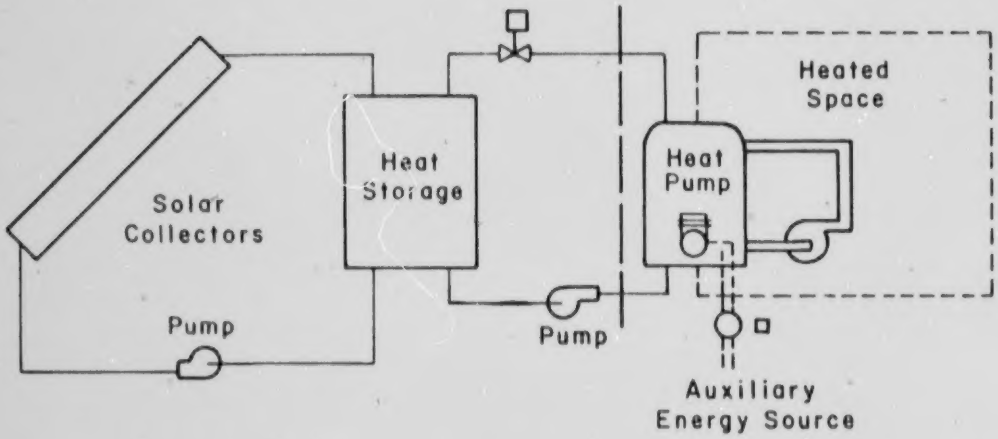

Solar Collectors
Heat Storage
Pump
Pump
Heat Pump
Heated Space
Auxiliary Energy Source

Figure 8-14. Simplified Diagram of a Solar Assisted Heat Pump System Series Arrangement

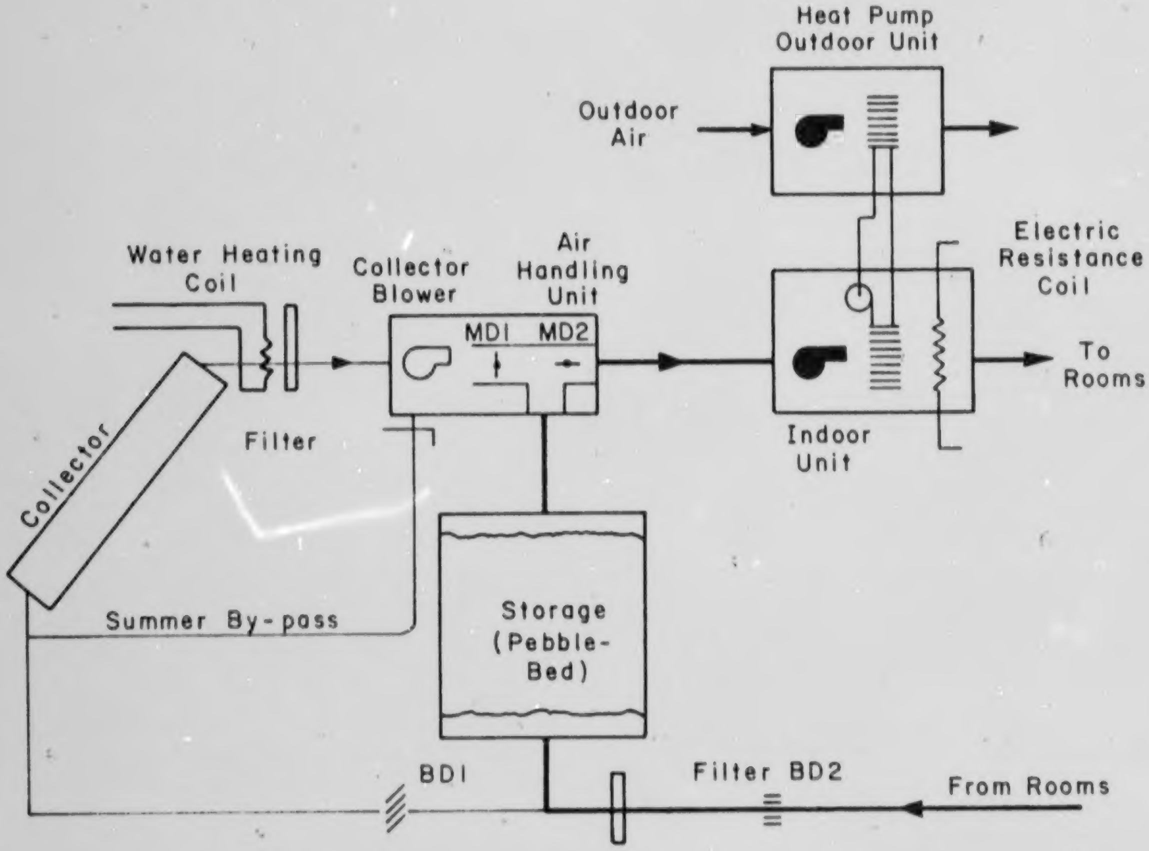

Heat Pump Outdoor Unit
Outdoor Air
Water Heating Coil
Collector Blower
Air Handling Unit
MD1
MD2
Electric Resistance Coil
To Rooms
Collector
Filter
Indoor Unit
Summer By-pass
Storage (Pebble-Bed)
BD1
Filter
BD2
From Rooms

Figure 8-15. Solar Heating System with Air-to-Air Heat Pump Auxiliary (Heating Building from Storage with Heat Pump Supplementary Supply)

TRAINING COURSE IN
THE PRACTICAL ASPECTS OF
SIZING, INSTALLATION, AND OPERATION OF SOLAR HEATING AND COOLING SYSTEMS
FOR
RESIDENTIAL BUILDINGS

MODULE 9

SOLAR SPACE COOLING SYSTEMS

SOLAR ENERGY APPLICATIONS LABORATORY
COLORADO STATE UNIVERSITY
FORT COLLINS, COLORADO

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GLOSSARY OF TERMS

absorbent	A liquid which combines chemically with a refrigerant
coefficient of performance	Ratio of heat removal rate to heat supply rate
refrigerant	Working fluid in a refrigeration system
ton of refrigeration	Heat removal at a rate of 12,000 Btu per hour

INTRODUCTION

The withdrawal of heat from the air within a building enclosure which results in a temperature lower than that of the natural surroundings is termed space cooling or refrigeration. The methods using solar energy are of particular interest in this module.

OBJECTIVE

The objective of this module is to develop understanding of the principles of solar space cooling systems. In order to test whether this objective is met by the trainee, as a minimum level of accomplishment, the trainee should be able to:

1. List the different cooling methods and
2. Describe the operation of cooling systems.

CATEGORIES OF SPACE COOLING METHODS

There are three categories of space cooling methods for residential buildings. They are:

1. Refrigeration
2. Evaporative cooling
3. Radiative cooling

Solar energy is directly useful only in refrigeration methods. Evaporative cooling and radiative cooling are indirectly related to solar energy in that they are dependent on climatic factors. The discussion in this module concerns principally refrigeration methods. Evaporative and radiative cooling are also briefly mentioned.

DEFINITION OF TERMS

The capacity of a refrigeration machine to cool room air is customarily referred in tons of refrigeration. A ton of refrigeration is the removal of heat at a rate of 12,000 Btu per hour. Another often used term in connection with refrigeration equipment is coefficient of performance, COP. The COP expresses the effectiveness of a refrigeration cooling system as the ratio of useful refrigeration effect to net energy supplied to the machine. The COP is determined by the simple equation below:

$$\text{COP} = \frac{\text{Heat energy removed}}{\text{Energy supplied from external sources}}$$

The COP of a mechanical vapor-compression refrigeration machine is characteristically about two and can be as high as four. The COP of a lithium-bromide-water absorption refrigeration machine is about 0.8 and more often operates in the range from 0.6 to 0.7. A COP less than 1.0 means there is more energy supplied to the machine than heat energy removed from the room air. From the cooling capacity and COP the energy consumption rate by the machine to produce the cooling effect can be determined by dividing the heat removal rate by the COP. For example, with a 3-ton absorption air chiller, having a heat removal rate of 36,000 Btu per hour, and a COP of 0.6, the quantity of heat needed at the generator is 60,000 Btu per hour (36,000 ÷ 0.6).

REFRIGERATION SYSTEMS

Refrigeration systems accomplish cooling by removing heat from the air as it comes in contact with a cold refrigerated surface. Conventional vapor-compression systems using electric motors are potentially convertible to systems with solar heat driven motors, and absorption refrigeration systems using gas fuel heat are potentially convertible to systems using solar heat. Of many possible systems, only the absorption systems are now available and are potentially economical in the near-term (next five years). Of the various types of absorption machines possible, the lithium-bromide-water unit is currently (1976) the only type which is commercially available for residential space cooling applications.

ABSORPTION REFRIGERATION

An absorption refrigeration machine uses heat energy to provide cooling. When a liquid mixture of refrigerant and absorbent is heated, the refrigerant is driven out of solution. The refrigerant flows from the generator through a condenser, expansion valve, and evaporator, then into an absorber, where it recombines with the absorbent. In a lithium-bromide-water absorption machine, water is the refrigerant and lithium bromide is the absorbent. An absorbent is a liquid which combines chemically with the refrigerant at low temperatures but will separate from the refrigerant at high temperatures. In the combination process, heat absorbed by the refrigerant is released.

The operating principle of a lithium bromide absorption cycle is explained with the aid of Figure 9-1. The cycle begins when water in the liquid mixture in the generator is boiled off and superheated with solar energy at temperatures between 170° and 210°F. Superheating of water is made possible by having very low pressure in the system. The superheated water vapor leaving the generator enters the condenser, where it is cooled to about 100°F by the cooling water from an outdoor cooling tower. The vapor condenses to a liquid and is then revaporized through

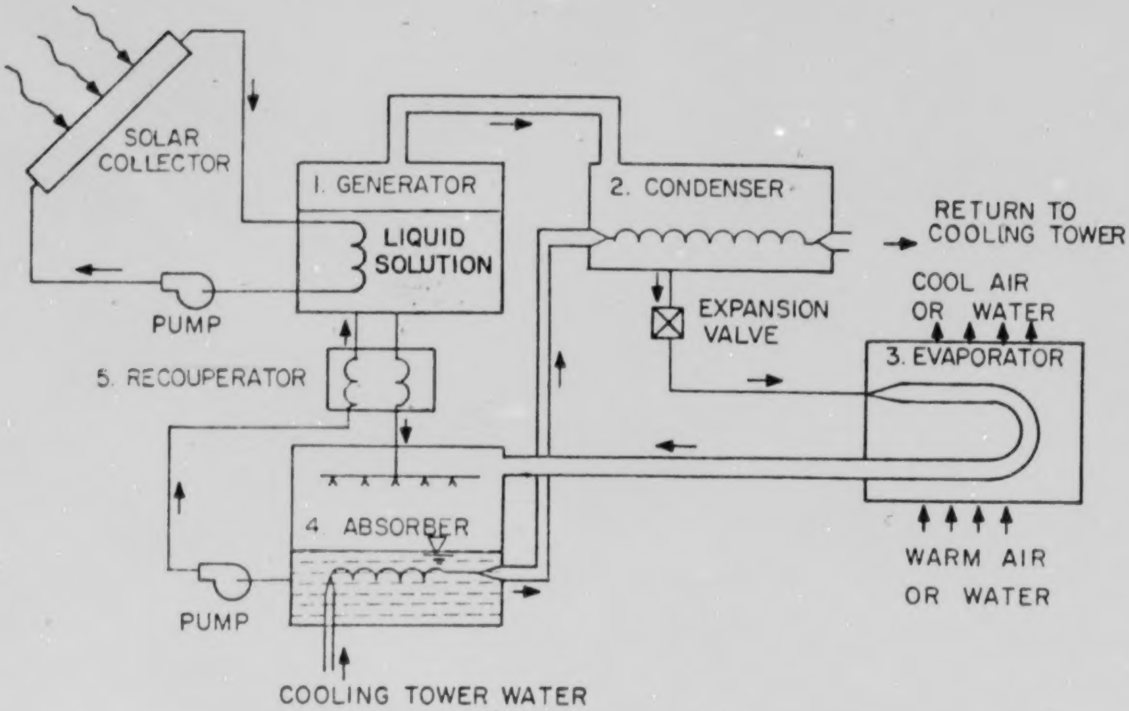
SOLAR COLLECTOR
1. GENERATOR
LIQUID SOLUTION
2. CONDENSER
RETURN TO COOLING TOWER
COOL AIR OR WATER
EXPANSION VALVE
3. EVAPORATOR
PUMP
5. RECOUPERATOR
4. ABSORBER
PUMP
WARM AIR OR WATER
COOLING TOWER WATER

Figure 9-1. Absorption Air Conditioner -- Schematic Drawing

an expansion valve which cools the vapor-liquid mixtures to a temperature of 40°F in the evaporator coils. The heat in the air or water which is brought in contact with the evaporator is removed by the cool refrigerant. The refrigerant then passes to the absorber where it recombines with the concentrated lithium-bromide solution from the generator at a temperature of about 100°F. In this recombination process, heat is released, and the heat is removed by the cooling water from the cooling tower. The dilute solution of lithium-bromide and water in the absorber flows by gravity, or is pumped, back to the generator and the cycle is repeated. The recouperator in the diagram is a heat exchanger which preheats the dilute solution as it flows from the absorber to the generator and at the same time cools the hot concentrated solution which flows from the generator to the absorber.

Temperature Restrictions

The operating temperature range of the hot water supplied to the generator of a solar-operated lithium-bromide-water absorption refrigeration machine is restricted from about 170°F to 210°F. The heat input to the generator must be sufficiently high to boil the refrigerant (water) from the solution in the generator. The temperature must be at least 170°F. The upper temperature is normally limited to 210°F because the hot water to the generator in a solar system is provided from storage and the temperature in storage will be less than the temperature of the concentrated lithium-bromide solution which flows from the generator to the absorber through the recouperator. If the temperature is too low in the recouperator, and the concentration of the lithium-bromide-water solution is high, the lithium-bromide will solidify in the outlet tube leading from the recouperator to the absorber and eventually in the generator as the water continues to be boiled off and the concentration of lithium-bromide increases. Provided the temperature in the generator is between 170°F and 210°F, the unit will operate satisfactorily.

Types of Lithium-Bromide-Absorption Chillers

There are two types of lithium-bromide-water absorption chillers. One type cools air directly at the evaporator coils and the other type cools water which contacts the evaporator coils. With an air chiller, room air can be circulated directly past the evaporator coils. The second type requires a fan coil unit with room air being cooled through the fan coil unit.

With a water chiller, the chilled water can also be stored, which enables a system to operate continuously over a longer period, which in turn is beneficial to the system COP, and the chilled water used together with direct cooling can provide for a large peak cooling load when needed. An air chiller does not provide for a convenient means of cool storage and thus the unit will cycle on when space cooling is needed and will shut off when it is not needed. When frequent cycling occurs, the COP of the cooling system will be very low. Continuous operation of the cooling system will maintain a high COP.

HEAT PUMP

A heat pump can be used as either a space heating or cooling unit. As a cooling unit, the device absorbs the heat from inside a building and rejects it to the outside air. The principles of operation are described in Module 8.

SOLAR RANKINE-CYCLE ENGINE

Instead of driving the compressor of a vapor-compression refrigeration machine with an electric motor, an alternative source of power for the compressor is a solar-powered engine. Solar heat can be used to vaporize an organic fluid to drive a turbine. The turbine is coupled to a compressor of the refrigeration machine, as shown in a schematic drawing of a simplified system in Figure 9-2.

Heat is supplied to the boiler by a solar collector. The fluid in the boiler is vaporized and the vapor drives the blades of the turbine. The rotating shaft of the turbine then drives a compressor for the vapor-compression refrigeration machine which produces the desired cooling effect. The vapor from the turbine is changed to a

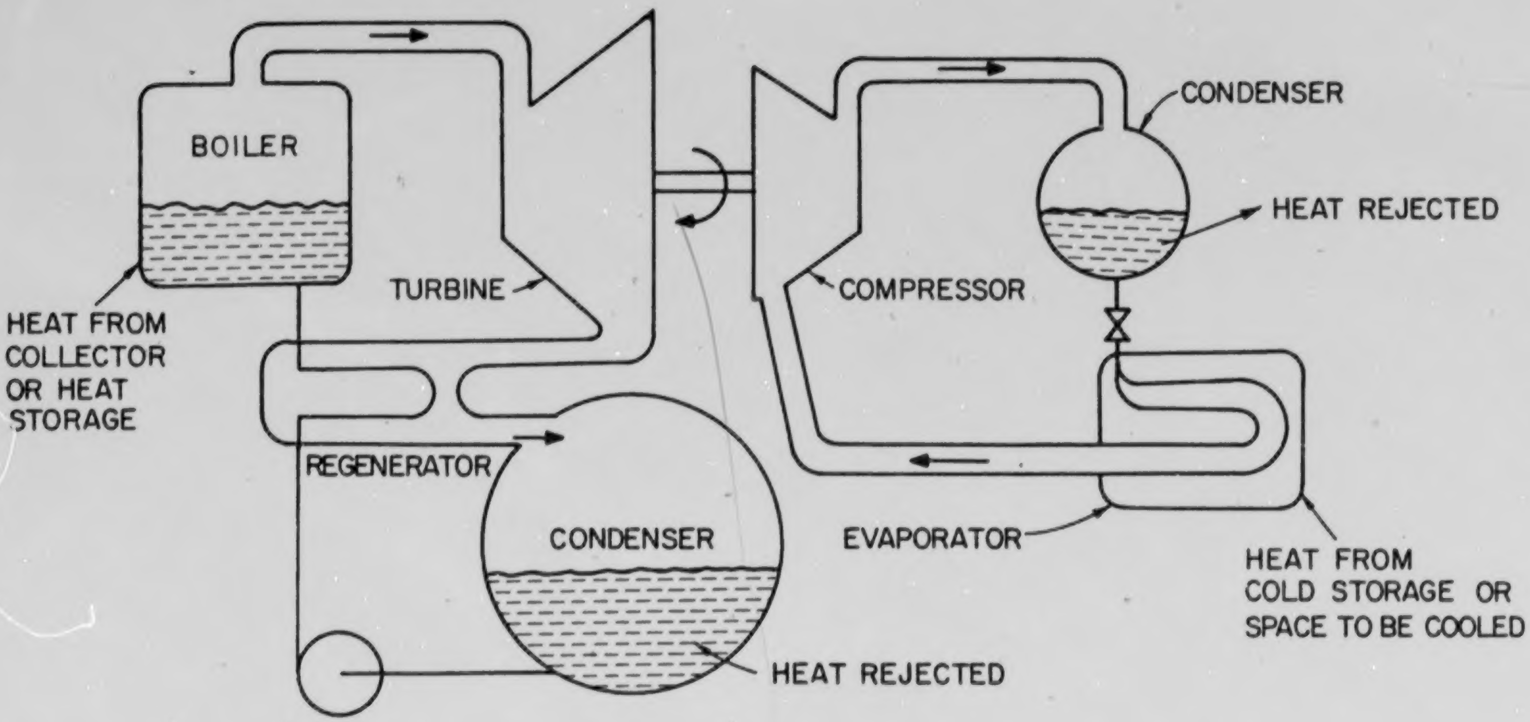
BOILER
TURBINE
HEAT FROM COLLECTOR OR HEAT STORAGE
REGENERATOR
CONDENSER
HEAT REJECTED
COMPRESSOR
CONDENSER
HEAT REJECTED
EVAPORATOR
HEAT FROM COLD STORAGE OR SPACE TO BE COOLED

Figure 9-2. Rankine-Cycle Vapor Compression System

liquid in the condenser and is pumped back to the boiler. The regenerator is a heat exchanger to recover some of the heat from the vapor ejected from the turbine. This machine is still in the experimental and developmental stages and is not yet available as an operational unit.

EVAPORATIVE COOLING

EVAPORATIVE COOLING THROUGH ROCK BED

A simple evaporator cooler can be used to cool warm air by passing the air through an air washer. Depending upon the velocity of air and wet-bulb temperature, warm air may be evaporatively cooled to a desired dry-bulb temperature. As an example, outside air at 100°F dry-bulb temperature and 70°F wet-bulb temperature (relative humidity 22 percent) can be cooled by an air washer to about 77°F. However, the relative humidity would be an uncomfortable 71 percent. Strictly speaking, evaporative cooling is not a solar system. However, because the rock bed of an air heating solar system can be used for storing "cool" in the summer-time, an evaporative cooling unit may be considered along with an air heating solar system.

An evaporative cooler coupled with a rock-bed storage unit is shown in Figure 9-3. Night air is evaporatively cooled and circulated through the rock bed to cool down the pebbles in the storage unit. During the day, warm air from the building can be cooled by passing the air through the cool pebble-bed. The dampers in the ducts are positioned to direct the circulation of air appropriately. When cooling is no longer achievable through the rock bed, the outdoor air can be cooled directly and delivered to the rooms. Evaporative cooling is practical only for

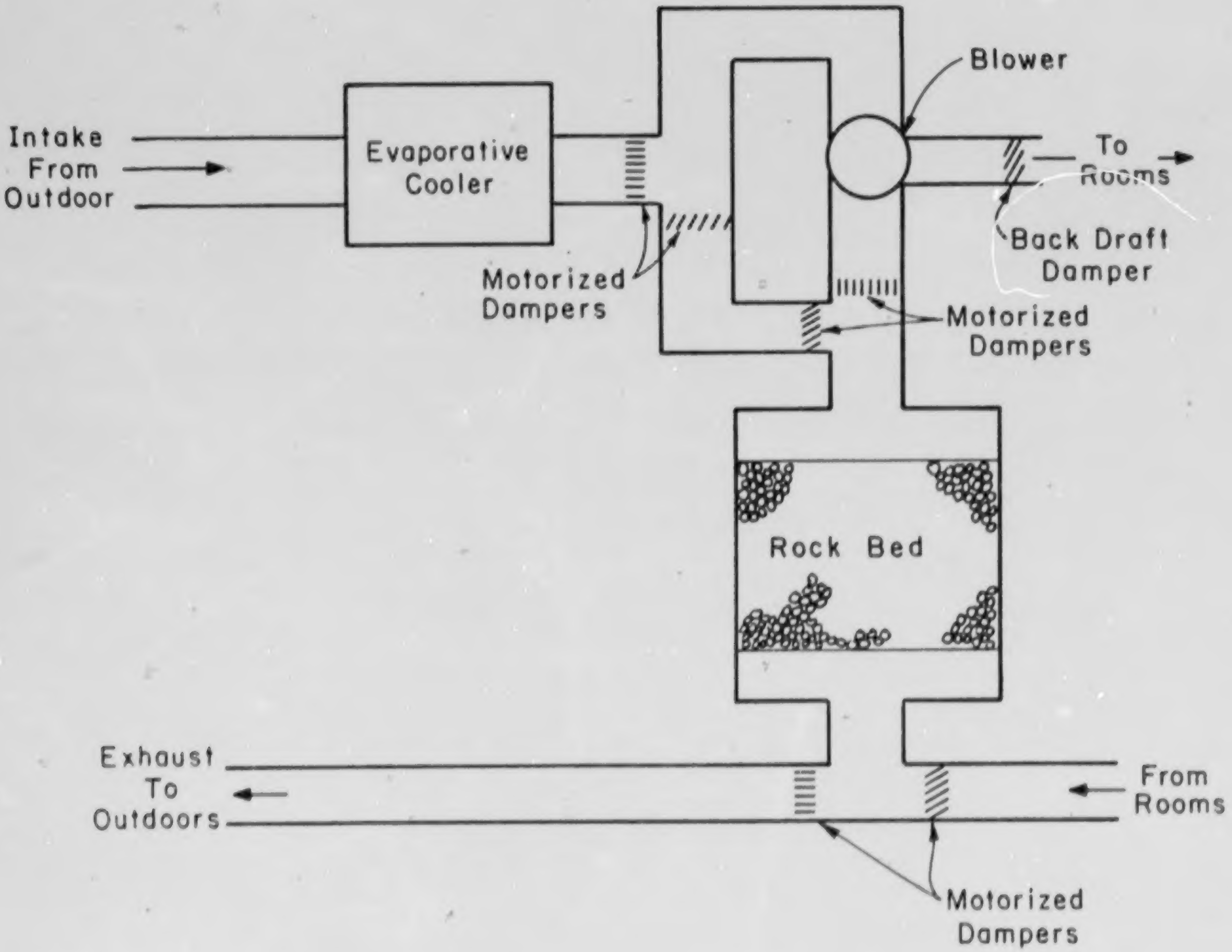
Intake
From
Outdoor
Evaporative
Cooler
Blower
To
Rooms
Back Draft
Damper
Motorized
Dampers
Motorized
Dampers
Rock Bed
Exhaust
To
Outdoors
From
Rooms
Motorized
Dampers

Figure 9-3. Evaporative Cooling with Rock Bed Storage

arid and semi-arid regions where the relative humidity and night-time temperatures are normally low.

TRIETHYLENE GLYCOL OPEN CYCLE DESICCANT SYSTEM

A system which provides cooling by dehumidification of the air is shown schematically in Figure 9-4. It is an open cycle system. Moist room air is dehumidified and cooled by triethylene glycol as the air flows through the absorber. The dehumidifed air passes through eliminators to remove the liquid glycol from the air and is further evaporatively cooled and redistributed to the rooms. The liquid desiccant which passes through the absorber picks up moisture from the building air and becomes diluted. This dilute triethylene glycol solution is regenerated to a concentrated form by using solar heat to remove the water and is returned to the absorber and recycled. At the stripping column the liquid mixture is sprayed into a stream of solar heated air. The heated air picks up the moisture from the glycol spray and is exhausted to the atmosphere. Liquid glycol droplets which are carried with the air stream are removed by the eliminators. If there is insufficient solar heat, then an auxiliary heater is used to heat the air stream. The triethylene glycol from the bottom of the stripping column returns to the absorber through heat exchangers to recover heat.

A wide range of solar heated air temperatures is possible to operate this system, from 84°F to 180°F. The higher the temperature, however, the higher will be the COP of the machine.

A liquid desiccant open-cycle system in large sizes, using conventional heat sources, is commercially available. Except for an experimental unit which was studied 25 years ago, this type of system has not been actively considered for residential space cooling systems.

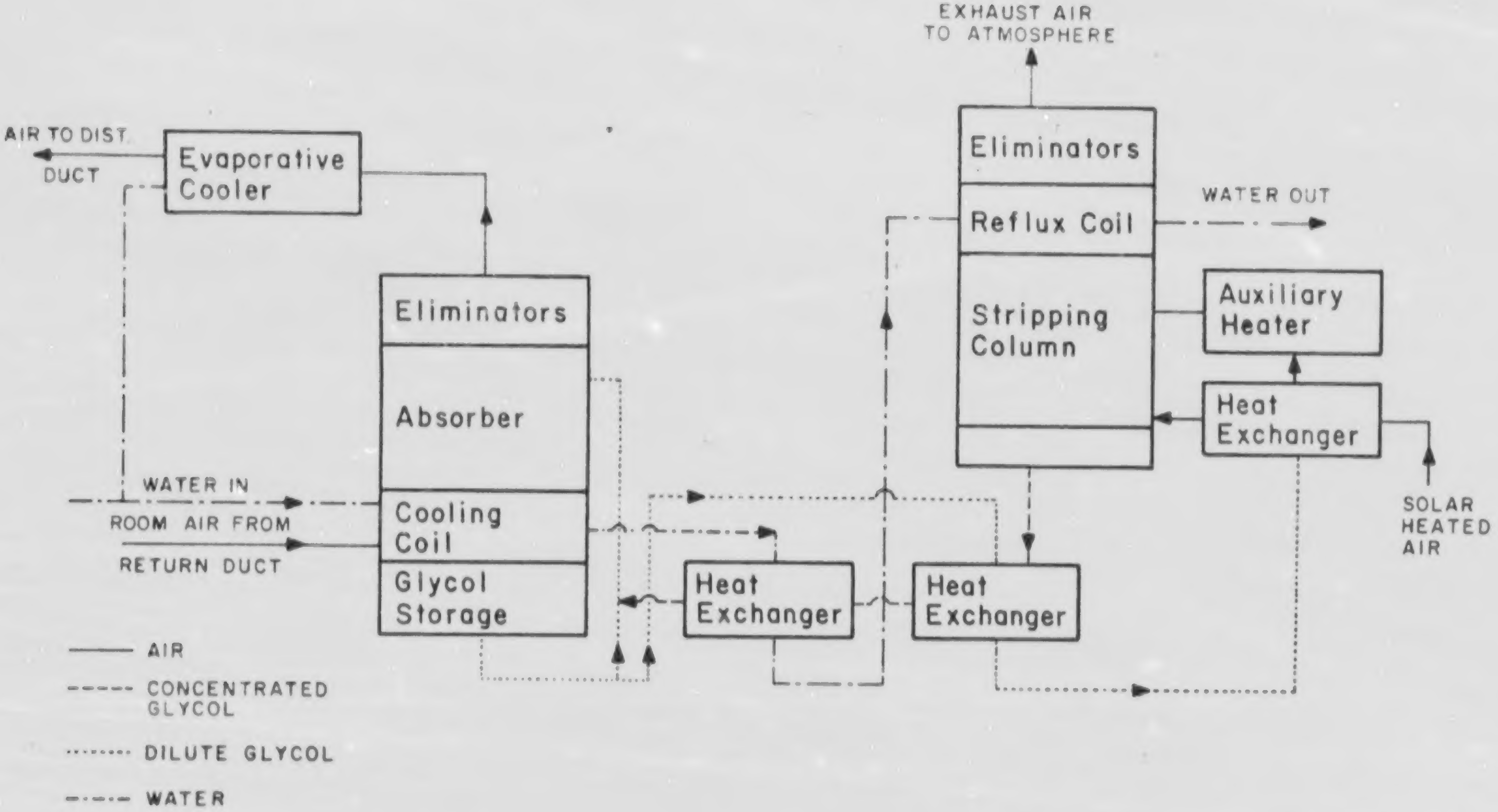
EXHAUST AIR
TO ATMOSPHERE
AIR TO DIST.
DUCT
Evaporative
Cooler
Eliminators
Reflux Coil
WATER OUT
Stripping
Column
Auxiliary
Heater
Heat
Exchanger
SOLAR
HEATED
AIR
Eliminators
Absorber
WATER IN
ROOM AIR FROM
RETURN DUCT
Cooling
Coil
Glycol
Storage
Heat
Exchanger
Heat
Exchanger
AIR
CONCENTRATED
GLYCOL
DILUTE GLYCOL
WATER

Figure 9-4. Schematic of Triethylene Glycol (Liquid Desiccant) Open Cycle Air Conditioning System

RADIATIVE COOLING

The use of a flat-plate collector to cool water or air by night radiation in the cooling season has been suggested as a possible way to cool a building. In principle, radiation from the absorber surface of a flat-plate collector to the cold night sky could cool the absorber surface and hence also the water or air circulating through the collector. The difficulty with this method is that a good collector is a poor radiator, therefore, using the same collector which collects solar heat for the heating season to cool air or water in the cooling season is not practical.

There are two solar houses, one in California and the other in Arizona, that utilize evaporative cooling and night-time radiation to regulate the temperature rise in residential buildings. The buildings have a shallow water pond on the roof with sectionalized retracting insulating covers over the pond. The covers are retracted at night to cool the pond by evaporation and radiation to the night sky. The covers are closed during the day to prevent solar heating of the pond. The cool pond absorbs the heat from the rooms below to keep the building space cool.

During the winter the shallow ponds are used for heating the building. The insulating covers are retracted during sunny days to collect solar heat in the pond and closed at night to prevent excessive heat loss from the pond. The stored heat in the pond then radiates uniformly into the living space below. At special locations in the country, this type of heating and cooling system is effective. However, in freezing climates, there are obvious difficulties when the outdoor temperature is very low.

A variation of the system is shown in Figure 9-5. Water in the radiative cooler on the roof of the house is cooled by evaporation and radiation. When the cold water in the storage tank can be cooled, the water is circulated to the radiative cooler. The radiative cooler, which is a water pond, will usually be dry during the day because when the pump is shut off, the water automatically drains into the cold water tank. An open cycle system such as this is subject to accumulation of debris and frequent cleaning will be necessary. Also, because the system will collect rainfall, an overflow must be provided to the storage tank, and in off-seasons, the melting snow should be suitably by-passed from the tank.

The building is cooled by circulating the cold water through a fan coil unit. When the temperature of the water at the bottom of the cold water tank is too high for efficient operation, the fan/coil unit and circulation pump are shut off.

Because of the continuous evaporation from the shallow roof pond, frequent addition of make-up water is necessary. Unless the water is drained and exchanged frequently, the salinity of the water will increase.

Draining of the shallow roof pond can be accomplished during the cooler seasons of the year when building air cooling and/or dehumidification is not required. Because the temperature of rain water would be close to the wet-bulb temperature of the air, in most instances, rain would assist in the cooling effort. Snow and/or melting snow should cause no problems during the winter, provided that the pipe draining the roof pond is large enough and the storage tank is protected from freezing.

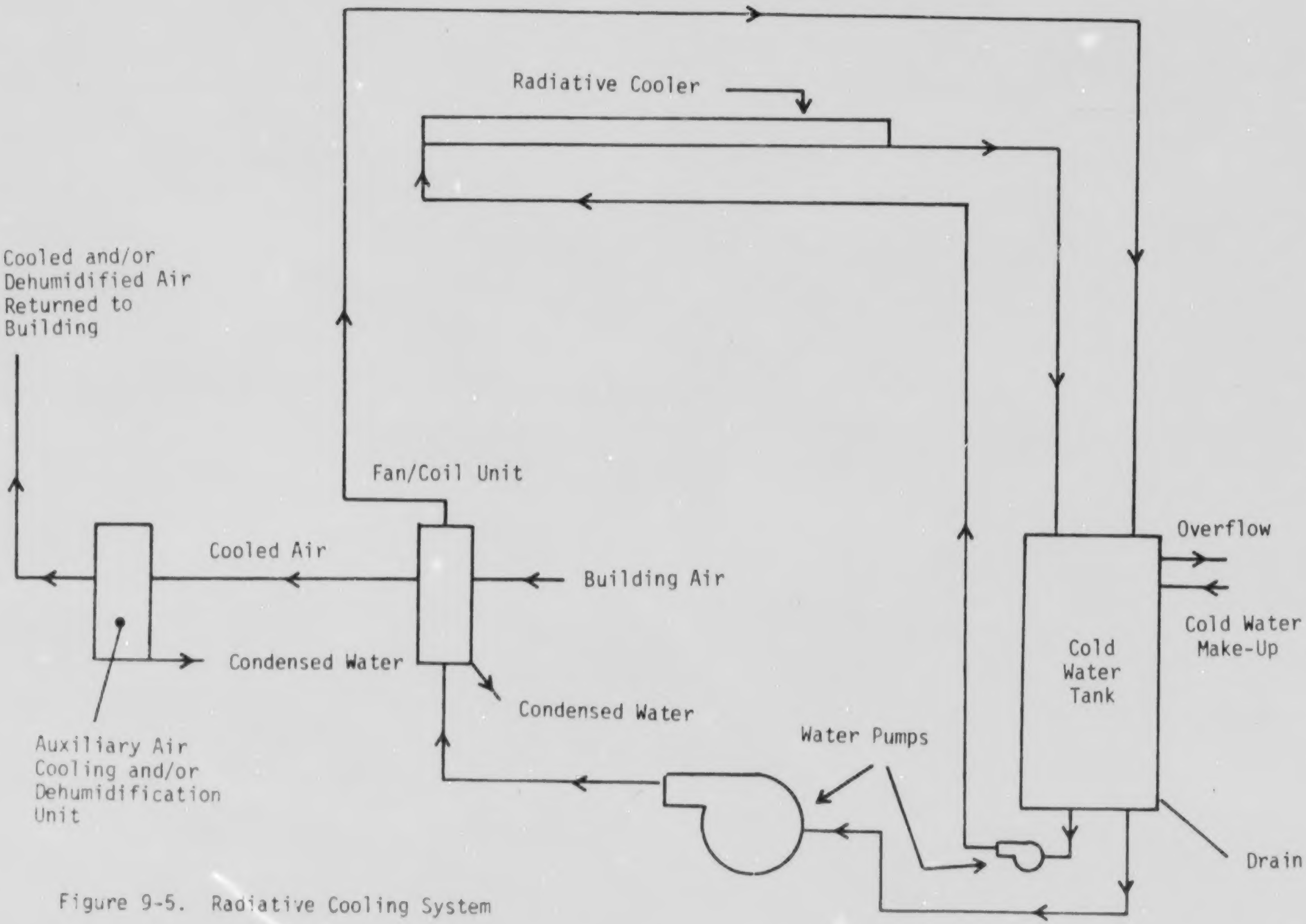
Radiative Cooler
Cooled and/or Dehumidified Air Returned to Building
Fan/Coil Unit
Overflow
Cooled Air
Building Air
Cold Water Make-Up
Cold Water Tank
Condensed Water
Condensed Water
Water Pumps
Auxiliary Air Cooling and/or Dehumidification Unit
Drain

Figure 9-5. Radiative Cooling System

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TRAINING COURSE IN
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MODULE 10

SOLAR HEATING AND COOLING SYSTEMS

SOLAR ENERGY APPLICATIONS LABORATORY
COLORADO STATE UNIVERSITY
FORT COLLINS, COLORADO

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INTRODUCTION

A solar space cooling system combined with a solar space heating system provides the opportunity to utilize the collectors and storage units during the entire year. In areas where both heating and cooling are needed in residential buildings, a combined system may soon become practical.

In a previous module, a space heating and cooling scheme using a shallow water pond on the roof of a building was described. Such a system has been shown to be workable in selected regions of the country where winter-time temperatures are mild. The difficulty in colder regions of the country is principally with freezing.

The arrangement and operation of solar cooling systems coupled to solar space and service water heating systems are discussed in this module. In arid and semi-arid regions, an evaporative cooling unit coupled with an air-heating solar system is a possible means to provide limited space cooling capability.

OBJECTIVE

The objective of the trainee in this module is to recognize the components and interfaces needed for a combined solar heating and cooling system and understanding of the operating characteristics of the system.

SOLAR HEATING AND ABSORPTION COOLING SYSTEM

A lithium-bromide-water absorption system is the only solar cooling unit described in this section. The trainee should be aware, however, that research is currently being conducted with other cooling units, such as an ammonia-water absorption system, and Rankine-cycle solar driven engines coupled to a vapor compression cooling machine. With further developments, such systems may become practical in the future.

SYSTEM COMPONENTS

A lithium-bromide absorption unit combined with a solar heating system is drawn schematically in Figure 10-1. The main components of the system that are common to both heating and cooling functions are the following:

1. Solar collectors
2. Storage tank
3. Auxiliary boiler
4. Duct coil and distribution ducts.

The additional components required for the solar cooling are:

1. Absorption chiller
2. Two cool storage tanks
3. Cooling tower
4. Circulation pumps.

The collectors are sized to provide the major fraction of the total annual heating load in the building. The collectors will then provide a substantial portion of the hot water necessary to operate the absorption chiller during the cooling season, provided that the collectors can deliver heat at temperatures necessary to operate the absorption chiller and can do so at reasonable efficiencies.

The storage tank should be sized in relationship to the collector area selected, and should not be less than 1.5 gallons, nor greater than

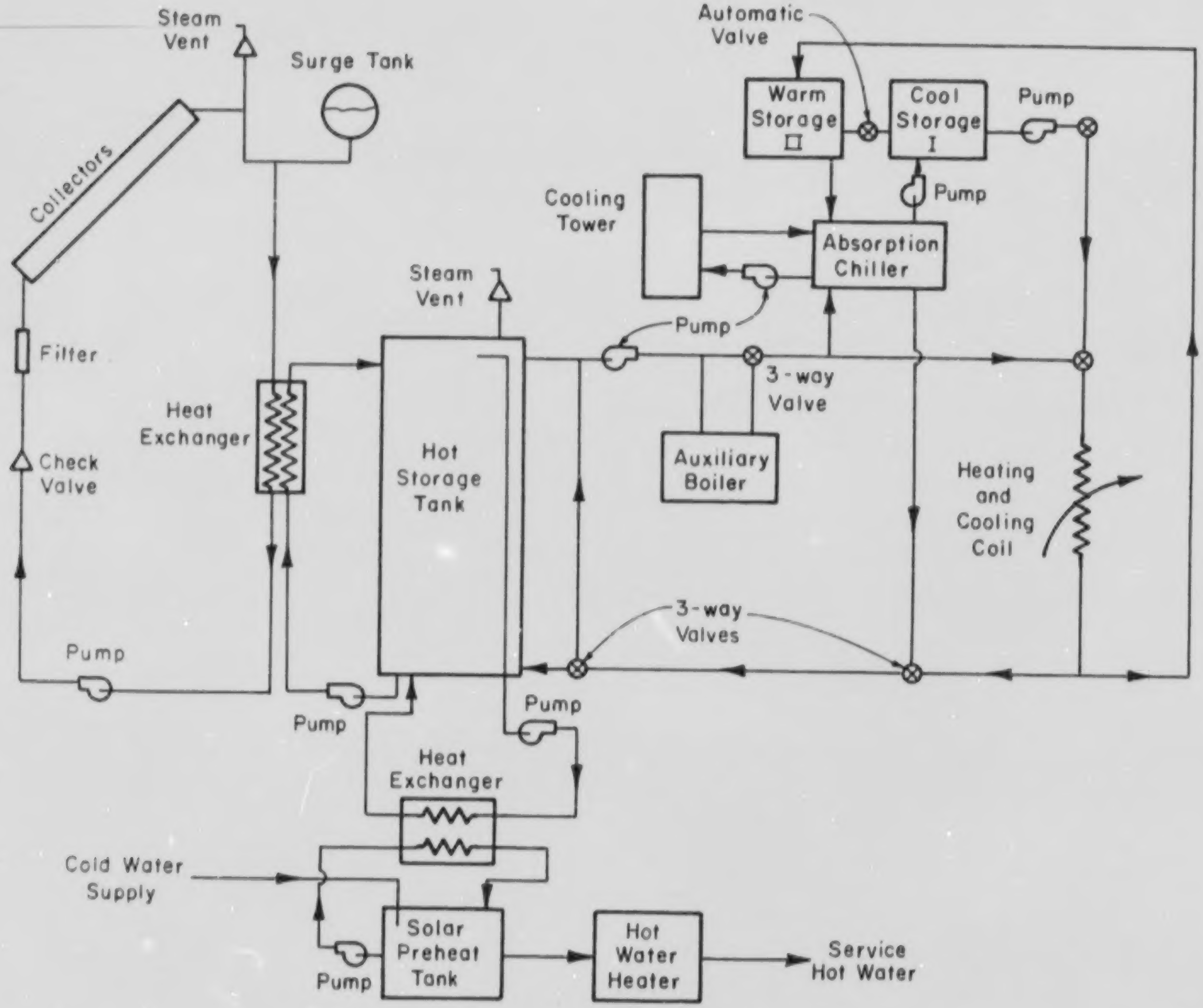
Steam Vent
Surge Tank
Collectors
Filter
Check Valve
Pump
Heat Exchanger
Pump
Steam Vent
Hot Storage Tank
Pump
Heat Exchanger
Cold Water Supply
Pump
Solar Preheat Tank
Hot Water Heater
Service Hot Water
Automatic Valve
Warm Storage II
Cool Storage I
Pump
Pump
Cooling Tower
Absorption Chiller
Pump
3-way Valve
Auxiliary Boiler
Heating and Cooling Coil
3-way Valves

Figure 10-1. Solar Heating and Cooling System

2.5 gallons per square foot of collector. A small storage tank size in relationship to collector area may cause frequent boiling in the collectors and in storage during the summer months, and in a larger storage tank, the water may not be hot enough to enable efficient operation of the absorption chiller. With a small storage tank, heat is wasted in steam when boiling occurs and a larger amount of auxiliary energy will be required to operate the chiller as compared to a properly sized storage tank. Similarly, with a large storage tank, the auxiliary boiler may be required more frequently because the storage tank temperature cannot be raised to the desired operating range of the absorption chiller.

The auxiliary boiler is used to provide heat when the temperature of the water in the storage tank is not sufficient either to heat the rooms to maintain the desired comfort conditions or to drive the absorption chiller unit. The boiler should be adjusted to deliver about 150°F water during the heating season to the heating coils, and about 190°F water during the summer to the absorption chiller.

The service water heating components will operate throughout the year without adjustment. Because the water temperatures in the heat exchange loops will be high, pumps and valves that can withstand high operating temperatures should be selected.

OPERATING CHARACTERISTICS

Collection Subsystem

The solar heat collection subsystem in the system shown schematically in Figure 10-1 will operate whenever the liquid temperature in the collector is greater than the storage tank water temperature by a preset amount, say 20°F, and the circulation pumps will shut off when the collectors cannot deliver heat at a temperature greater than the water in the storage tank. Because there is a heat exchanger in the heat collection loop, the temperature differential for shut off will be about 5°F. The heat exchanger is used to separate the collector fluid from the storage fluid and antifreeze can be added to the collector fluid.

During the heating season, the temperature range in the storage tank will be from about 90°F to 150°F, and with 1000 gallons of water, there will be 500,400 Btu of heat available in storage. During the cooling season, the useful range of water temperature in the storage tank will be from 180°F to 210°F, and, again, in 1000 gallons of water, 250,000 Btu of useful heat can be stored to drive the absorption unit. Although the absorption chiller cannot be operated with water temperature less than 180°F in the storage tank, the service water heating system can extract the heat usefully.

Heating Subsystem

The water from the upper part of the storage tank is pumped through the heating coils and returned to the bottom of the storage tank. The heating coil can be in the main duct in a central heating system or separate fan coil units may be used in different zones of the building. There will be longer pipes and more valves required for a fan coil heating unit than are needed for a coil in the central distribution system.

When the temperature of the water in storage is not sufficient to deliver heat at a rate sufficient to maintain the comfort level in the rooms, the auxiliary boiler engages automatically to deliver hot water to the heating coils. It is recommended to arrange the piping so that when the auxiliary boiler is on, the return water from the coils by-passes the storage tank. The storage water temperature will be low when the auxiliary boiler is delivering hot water and the return water temperature from the heating coil will be higher than the storage tank temperature. By-passing the storage tank will prevent heating the large volume of water in the storage tank with auxiliary energy.

The thermostat in the building is the sensor which drives the heating system. A dual contact unit is required for the system shown in Figure 10-1. As the room cools, the first contact will engage the circulation system from the storage tank and, if the room temperature continues to fall, the second contact will engage the auxiliary boiler. When the room temperature rises to an adequate level, the heating cycle is shut off.

Let it be assumed that the design heating load for the house is 50,000 Btu/hr with a design outdoor temperature of 0°F, and the average heating degree-day in January is 35 degree-days. The heating load for the day would then be determined by:

$$\left(24\ \frac{\text{hours}}{\text{day}}\right)\left(\frac{\text{Design heating load}}{\text{Design temperature difference}}\right)(\text{degree-day})$$

or

$$\left(24\ \frac{\text{hours}}{\text{day}}\right)\left(\frac{50{,}000\ \text{Btu}}{68-0\ \text{hr}\cdot{}^{\circ}\text{F-day}}\right)(35^{\circ}\text{F-day}) = 617{,}650\ \text{Btu/day}$$

With the water temperature range in a 1200 gallon storage tank of 95°F to 140°F, there will be enough heat stored (450,360 Btu) to supply about three-fourths of the heat that is needed during the day, or about 18 hours. Thus the solar collector area should be sized so that with six hours of solar heat collection during the day, there will be about 18 hours of heat delivery from storage to the building through the evening hours and during the night until solar energy can be collected again the following day.

When the average ambient air temperature is less than that assumed in the foregoing computations, more heat will be required to heat the building than can be delivered from the solar system, but there will also be days with higher average temperature and the solar system can deliver more heat than is needed to maintain the comfort level in the house. When averaged over a heating season, the solar system should provide between 60 and 80 percent of the space heating needs.

Service Water Heating Subsystem

Hot water from the top of storage is pumped to a double-walled heat exchanger and returned to the bottom of the storage tank. Simultaneously, the water from the solar preheat tank is circulated through the heat exchanger and back to the top of the preheat tank. The system operates whenever the temperature of water in the storage tank is greater than the water temperature in the preheat tank by a preset amount, and shuts off when useful heat cannot be delivered from storage to the preheat tank, or the preheat tank temperature has reached a limiting high temperature, say 140°F.

During the heating season, the water temperature in the storage tank will be frequently less than 140°F; thus an auxiliary hot water heater is necessary to assure delivery of hot service water. The solar heat is thus used to preheat the cold water from the water main before entering the hot water heater. During the summer, the water temperature in the storage tank will be generally greater than 180°F; thus the preheat tank can be kept at high temperature with only infrequent necessity for auxiliary heating.

Suppose that an average daily use of service water in the household is 75 gallons per day. Also assume that the water temperature from the main is about 60°F and desired water temperature at delivery is 140°F. The daily quantity of heat necessary to raise the temperature of the service water from 60° to 140°F will be about 50,000 Btu. Delivery of 50,000 Btu from storage to the service water heating system will cause a drop in storage water temperature of 6°F (assuming no heat is delivered from the collectors to storage in the interim period). If the storage tank temperature is less than 140°F, the useful heat delivered to the service water heating system will be less than that indicated above, and the auxiliary heating unit will be required to maintain the desired water temperature in the hot water heater. In the summer-time there will be enough heat in the solar heated tank to supply the heat necessary for the service hot water.

An alternate arrangement to supply solar heat to the service water heating subsystem in the summer period is shown in Figure 10-2. Because it is desired to maintain the temperature of the water in the storage tank above 180°F for the purpose of operating the absorption cooler, the solar collection system will not operate unless the collectors can deliver water temperatures greater than, say, 190° to 200°F. Thus the collector system will not begin to operate until late morning and will shut off early in the afternoon. The arrangement shown in Figure 10-2 will utilize the solar collectors for service water heating early in the morning and also late in the afternoon because the maximum service hot water temperature required is only about 140°F. The use of the collectors in this manner will reduce the quantity of heat withdrawn from the storage tank for service water heating. The arrangement will be less useful in the winter months because the water temperature ranges in the storage and preheat tanks are about the same, so that if solar heat is deliverable to the preheat tank, it will also be deliverable to the storage tank.

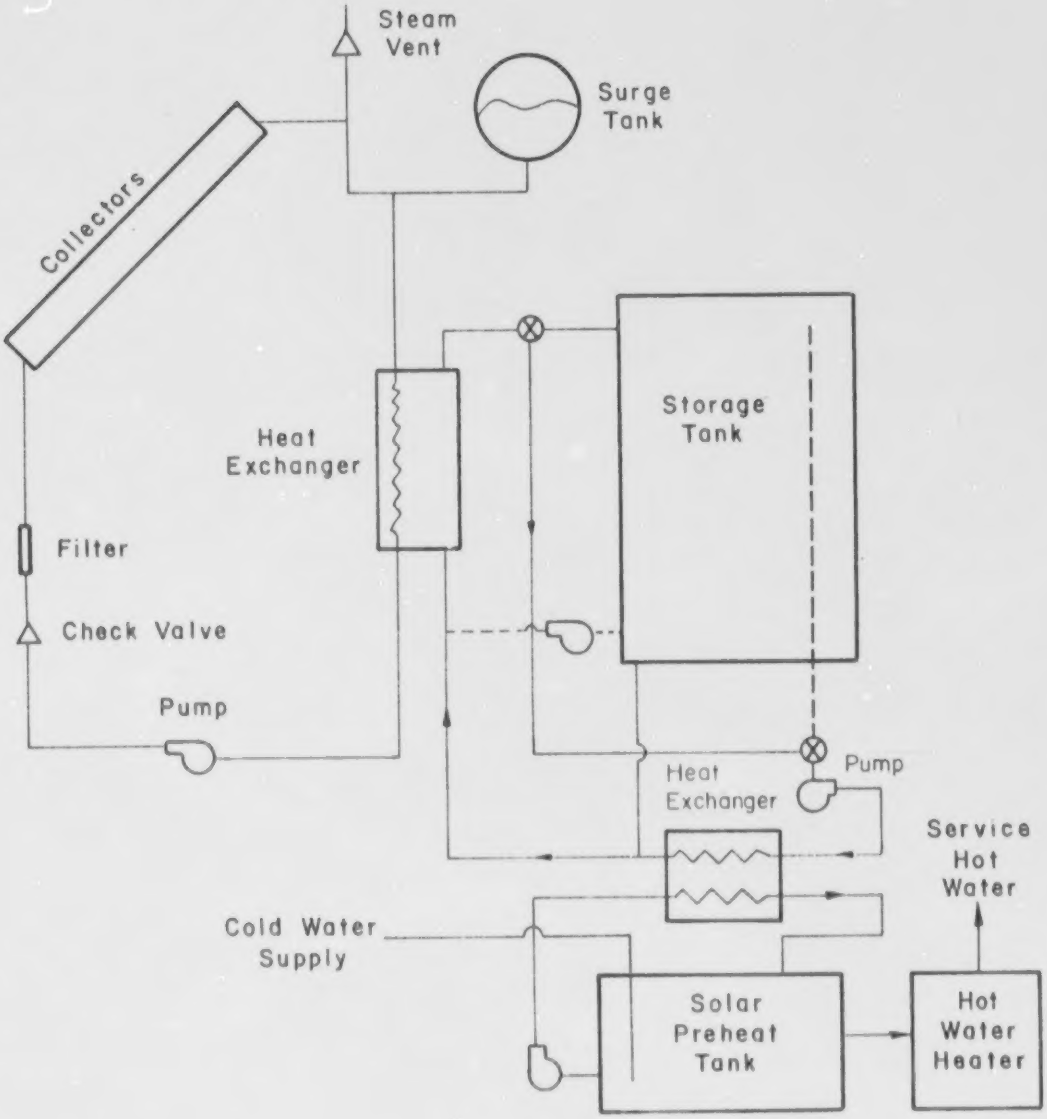
Steam Vent
Surge Tank
Collectors
Storage Tank
Heat Exchanger
Filter
Check Valve
Pump
Heat Exchanger
Pump
Service Hot Water
Cold Water Supply
Solar Preheat Tank
Hot Water Heater

Figure 10-2. Alternative Summer Time Arrangement for Solar Heating Service Hot Water

Cooling Subsystem

The water from the top of the hot storage tank is pumped through the generator of the absorption chiller and is returned to the bottom of the storage tank as shown in Figure 10-1. The three-way valves are positioned to prevent hot water passage through the coils and by-passing the storage tank. When the temperature of the water in the storage tank is insufficient to operate the chiller (the minimum operating temperature in the generator is about 170°F), the auxiliary boiler is used to provide the heat to the generator. When the auxiliary boiler is used, the three-way valve directs the flow to by-pass the return water around the storage tank.

As the circulation pump for hot water is started, the circulation pump for the cooling tower also starts. After a period of about ten minutes when the evaporator coils are cooled, the circulation pump for the chilled water storage is started. There are two interconnected cool water storage tanks. This arrangement provides for a measure of stratification because the temperature of water in storage tank I will be colder than the water temperature in storage tank II.

When cooling is needed in the building, the coldest water from storage tank I is delivered to the cooling coils in the duct, or to the fan coil units, and warm water returns to storage tank II. The warm water from tank II returns to the absorption chiller to be recooled. When cooling is not required in the building, the warm water in storage tank II is chilled and stored in tank I, and the chiller continues to operate until tank I is fully charged with cold water. As cooling is needed in the house, the chilled water circulation pump delivers the cold water to the cooling coils and returns warm water to storage tank II. This circulation will continue as long as cooling is required and there is sufficient cool water in storage. When the cool water in storage tank I reaches a pre-set level (approximately one-third full) the absorption chiller will restart and deliver cold water to storage tank I and to the load and continue to operate until storage tank I has been recharged.

In the cooling system arrangement, the absorption chiller will operate continuously over longer periods of time after starting, which is beneficial to the overall coefficient of performance (COP) of the system. Intermittent cycling of the absorption chiller may reduce the effective COP from 0.7 to, say, 0.3 because heat is wasted during each start and stop cycle.

An alternative arrangement of a cooling subsystem is shown in Figure 10-3, where two cooling coils are used and the cold water in storage can be used simultaneously with cold water from the absorption chiller to meet a heavy peak cooling load. When cold storage tank I has been charged with cold water, and the heat removal rate from room air is not sufficient by either the chiller or circulation of the stored cold water alone to maintain comfort conditions, the cooling capability of both the absorption chiller and cold storage can be combined. The arrangement shown, while potentially useful, has not been tested and performance data are not available to indicate the advantages and operating difficulties of the system.

The heat delivery rate to a nominal 3-ton absorption chiller with a COP of about 0.7 is 51,400 Btu/hr (36,000 : 0.7). If the difference in water temperature between the entrance and exit to the generator is 10°F, the flow rate through the generator must be about 10 gpm. The heat removal rate from the absorption chiller required is 87,400 Btu/hr (51,400 Btu/hr from the generator plus 36,000 Btu/hr at the evaporator). If the cooling water from the tower is at a temperature near 75°F, and

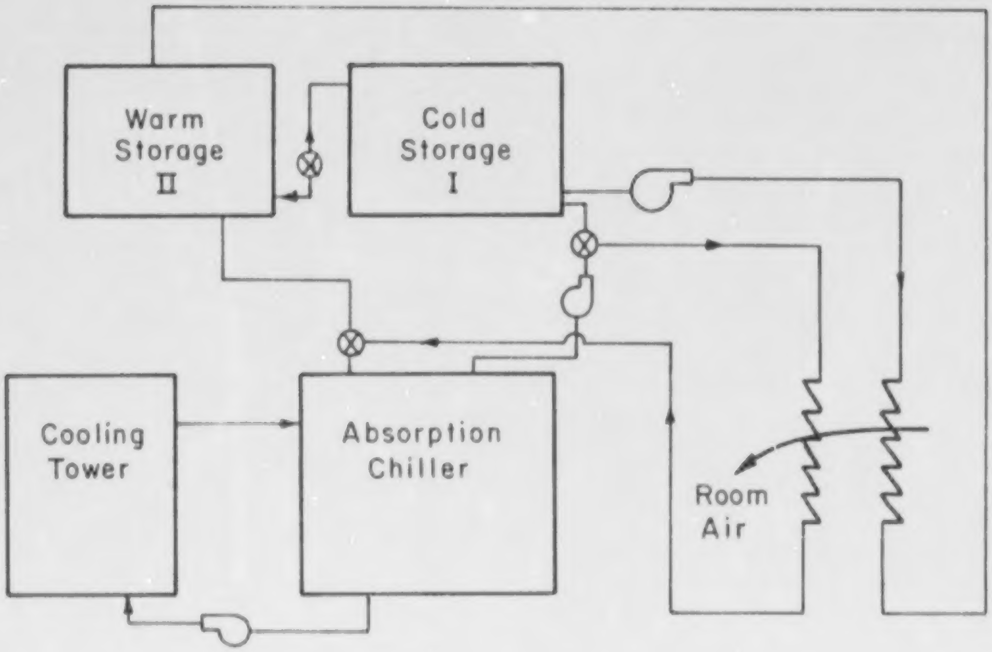

Figure 10-3. Alternative Cooling Subsystem with Two Cooling Coils

the water temperature is delivered at about 90°F, the circulation rate to the cooling tower should be about 12 gpm. Assume that the hot storage tank contains water at 210°F and the system will operate until the temperature drops to 180°F; then there is enough heat in 1000 gallons of water storage to operate the chiller for about five hours.

The quantity of water in cool storage should be sufficient to prevent frequent cycling of the chiller. If two 250-gallon cold storage tanks are used, about 2.5 hours of continuous operation of the chiller is needed to chill the water in cold storage from about 65°F to 45°F. With chilled water storage, solar collectors to operate the system during the day and 1000 gallons of hot water storage, the cooling system can operate continuously from mid-morning until late evening hours.

INSTALLATION CONSIDERATIONS

The heating and cooling system should be assembled so as to minimize piping lengths from the storage tank to the heating coil, storage tank to the service water heating subsystem, and from the storage tank to the absorption chiller. The shorter the pipe lengths, the less will be the heat losses and pumping head. To minimize operating costs, the pump heads, hence power requirements, should be as small as possible.

The pipes should be well-insulated to minimize heat losses and heat gains and the hot and cold storage tank should also be well-insulated. Despite well-insulated surfaces, there will be heat flow into the building enclosure from the solar equipment. During the heating season, the heat losses from the equipment will be distributed into the building, but during the heating season the heat losses will add to the cooling load. It is recommended therefore that the solar equipment be assembled in a single room which can be vented outdoors during the cooling season and indoors during the heating season.

Equipment such as pumps and valves which require maintenance should be located so that they are easily accessible. The absorption chiller will require at least annual maintenance and should be located with sufficient room around the unit to facilitate maintenance.

Centrifugal pumps are recommended in the heating and cooling system because they are pressure-limited. Should the automatic valves become inoperative, or lines become clogged for some reason, the pressure created by the pump will not be excessive so as to rupture the pipes.

The pumps should be located to cause self-priming and with sufficient head at the suction side to prevent vapor locking in the pump chamber.

Care should be exercised during assembly of pipes, joints, and valves and leak tests should be performed before insulation is applied. With reasonable care during assembly, much time and cost can be avoided in repairing leaks.

SOLAR HEATING AND EVAPORATIVE COOLING SYSTEM

A solar air heating system with rock bed storage and an evaporative cooling unit is described in this section. Although heat can be stored in materials other than rocks, pebble-bed storage is preferred because rocks are inexpensive and readily available. The rock bed used for heat storage is also used for cool storage.

SYSTEM COMPONENTS

A schematic diagram of an air heating and nocturnal cooling system is shown in Figure 10-4. The cooling subsystem does not depend upon solar energy, but utilizes the rock bed for storage of cooling capability during the night.

As with the liquid heating solar system with absorption cooling, the collectors and storage volume are sized to meet the heating needs. A rock bed storage unit will normally be sized for 50 to 100 pounds (0.5 to 1.0 cubic foot) of rock for each square foot of collector, and constructed with sufficient depth to assure thermal stratification.

The direction of air flow through a rock bed is normally vertical for best operation. During the heat storage cycle, heated air is usually

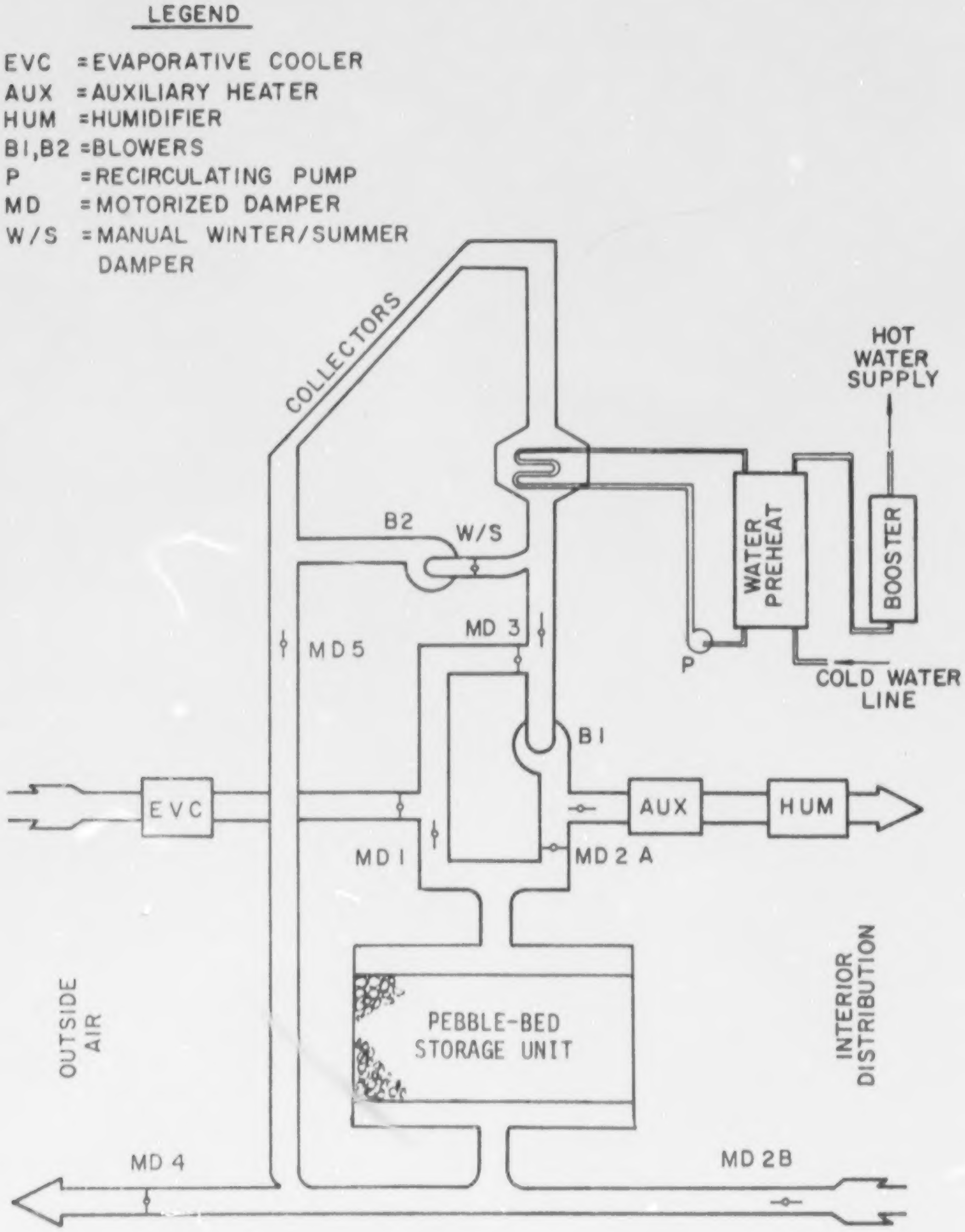
LEGEND
EVC = EVAPORATIVE COOLER
AUX = AUXILIARY HEATER
HUM = HUMIDIFIER
B1,B2 = BLOWERS
P = RECIRCULATING PUMP
MD = MOTORIZED DAMPER
W/S = MANUAL WINTER/SUMMER DAMPER
COLLECTORS
HOT WATER SUPPLY
WATER PREHEAT
BOOSTER
B2
W/S
MD 3
MD5
P
COLD WATER LINE
B1
EVC
AUX
HUM
MD1
MD2 A
OUTSIDE AIR
PEBBLE-BED STORAGE UNIT
INTERIOR DISTRIBUTION
MD 4
MD 2B

Figure 10-4. Schematic of an Air Heating System with Evaporative Cooling

delivered to the top of the gravel bed, and discharged at the bottom. In a distance of two to three feet in the direction of air travel, all of the heat in the air is transferred to the rocks. To provide for adequate heat storage during the day, the depth of the rock bed should be about five to six feet.

A single blower in the system shown in Figure 10-4 is used both to heat and cool the building. To enable service water heating during the summer months, a second blower is needed to circulate hot air through the collectors and the air-water heat exchanger.

The auxiliary heater in the system is used to supplement the solar heat or to carry the full load when solar heat is not available. The humidifier is used during the heating season to condition the air delivered to the rooms.

OPERATING CHARACTERISTICS

Collection Subsystem

The solar collectors heat the air circulated by a blower and the hot air is forced through the pebble-bed, usually from the top toward the bottom. As the hot air passes through the pebble-bed, the heat is given up to the rocks and the air exits from storage at room temperature. The bottom of storage is never less than room temperature because during the heat delivery cycle, the room air flows from the bottom toward the top. The cool air returns to the collector to be reheated. With an air flow rate of 2 cfm per square foot of collector, the air temperature rise will be 4.5 to 5.0°F for each foot of travel through the collector. Thus with a 16 foot length of air travel through the collector, the temperature rise is 70° to 80°F. The quantity of heat stored in a pebble-bed is about two-thirds of full capacity because of the stratification. With 20 tons of rock, and 70°F temperature rise, about 375,000 Btu is stored. Fully charged, about 560,000 Btu can be stored in 20 tons of rock.

Heating Subsystem

An air heating solar system can be arranged to heat the rooms directly from the collectors without passing through storage. To heat the rooms from storage, the air flows from the cold toward the hot end and the hottest air available from storage is delivered to the rooms. When the heat in storage is insufficient to maintain comfort conditions in the building, the auxiliary heater adds to the solar heat. Because the room air is always circulated through storage, all the available heat in the storage unit is utilized.

Service Water Heating Subsystem

The service water is preheated by solar heated air through an air-to-water heat exchanger placed in the hot air duct from the collectors. The pump which circulates the water is controlled by a differential thermostat. When the air temperature from the collector is greater than the water temperature by, say, 20°F, water is circulated through the heat exchanger and heat is extracted from the air and transferred to the water. If the water temperature reaches about 140°F, or the air temperature is less than 5°F warmer than the water temperature, the pump is stopped.

With a water circulation rate of 1 gpm, and temperature rise of 10°F in the water, the rate of heat extraction from the air is about 5,000 Btu/hr. Thus, when the solar collector is delivering 70,500 Btu/hr, the heat flow rate remaining in the air is 65,500 Btu/hr.

Cooling Subsystem

The evaporator cooler in the system of Figure 10-4 is used to cool the rock bed storage during cool night-time hours. During the day when cooling is required in the building, the room air is drawn through the cool storage bed and the cooled air is distributed back to the rooms.

If the rock bed can be cooled to 55°F during the night, and the building air is to be maintained at 75°F during the day, the cooling rate provided with 1200 cfm air circulation rate is about 25,000 Btu/hr, or 2.1 tons. The cooling capacity stored in the rock bed with 20 tons of rock is about 110,000 Btu. At a cooling rate of 2.1 tons, there are about 4.5 hours of cooling capability from the cool pebble-bed.

The evaporator cooler is sized by the air flow rate, and temperature of the cooled air depends upon the outdoor dry-and wet-bulb air temperatures. With low humidity of the outdoor air, the evaporator cooler can be used during the day to cool the room air. The cooled air temperature, however, will not be as low as at night.

INSTALLATION CONSIDERATIONS

The air heating system will occupy three times as much floor space as a liquid heating and cooling system and requires careful planning to minimize wasted floor space. The dampers and blowers can be arranged in a compact air handler unit and the ducts to the collectors, storage, and the rooms connected to appropriate ports in the air handler.

Care should be exercised in assembling the storage unit and the ducts to prevent air leakage. The joints in the storage box should be caulked and the duct joints should be taped or hard casted. Air leakage from ducts within the conditioned space is not lost, but constitutes unregulated heating and is therefore wasteful.

The blower should be arranged so that the air pressure through the collector is subatmospheric. Any air leak in the collector array will cause cold air to be drawn into the collectors, which would be mixed with the heated air. A quantity of air equal to the inflow leak will be discharged outside from the conditioned space. If the air through the collector is under pressure and there is a leak in the collector array, hot air would be discharged and cool air would be drawn into the conditioned space. While the quantity of air leakage may be the same in both cases, the quantity of heat lost is greater for the latter because hot air, at say 140°F, is wasted from the system. In the former arrangement, room air at 70°F is wasted to the outdoors. While no leak is desirable, the former arrangement loses less heat from the system than the latter.

The duct leading to the evaporative cooler and discharging outdoors should be positively closed during the heating season. All air dampers leak some amount and cold air drawn into the system through the cooling ducts will reduce the air temperature in the system. Likewise, a slide damper should be inserted in the by-pass duct and for summer-time service water heating.

TRAINING COURSE IN
THE PRACTICAL ASPECTS OF
SIZING, INSTALLATION, AND OPERATION OF SOLAR HEATING AND COOLING SYSTEMS
FOR
RESIDENTIAL BUILDINGS

MODULE 11

SOLAR SYSTEM CONTROLS

SOLAR ENERGY APPLICATIONS LABORATORY
COLORADO STATE UNIVERSITY
FORT COLLINS, COLORADO

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INTRODUCTION

The only adjustable control for the solar heating and cooling system by the building occupant is the thermostat in the building. However, there are many important controls in solar systems that automatically control the pumps and blowers, valves and dampers, and the auxiliary heaters to collect and deliver the heat. The operation and installation principles of the various sensors needed for control are discussed in this module.

OBJECTIVE

The objective of the trainee is to understand the function, mechanics, and installation of control systems. At the end of this module the trainee should be able to:

1. Identify control functions,
2. Describe and diagram a control method,
3. Recognize control methods and hardware,
4. Specify control components,
5. Install and maintain control systems.

CONTROL FUNCTIONS

BASIC CONTROL STRATEGY

The basic function of the controller in a solar system is to collect as much useful heat as possible and to deliver it when required to meet the demands of the building. The overall efficiency of the total system can be strongly influenced by the controller.

A block diagram of a controller is shown in Figure 11-1. The three basic components of the controller are the sensor subsystem, the comparator

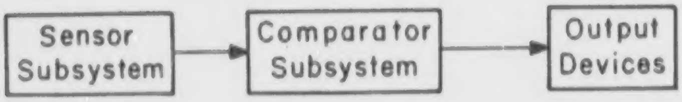


Figure 11-1. Block Diagram Representation of a Control System

subsystem, and the output subsystem. The function of the sensor subsystem is to measure temperatures and send this information to the comparator subsystem. The comparator subsystem makes the decisions regarding the control of output devices, such as the turning on and off of blowers and pumps and the opening and closing of valves and dampers.

At the present time most commercially available control systems are of the "on-off" type. That is, a pump or blower is either off or on at full capacity. The decision to turn the device on or off is based on temperature differences. For example, consider the schematic representation of a solar system (hydronic type) shown in Figure 11-2. The temperature sensors are indicated by S1, S2, S3, and S4. S1 measures the temperature of the fluid at the collector (or the temperature of the absorber plate, depending on the type of mounting), S2 measures the temperature of the water in storage, S3 measures the room temperature in the building (there could be several room temperature sensors), and S4 measures the temperature of the water in the preheat tank for service hot water. We shall consider how S1 and S2 are typically used in an "on-off" controller to control the collector pumps, shown as Pump Number 1 and Pump Number 2 in Figure 11-2. Suppose that the temperature variation throughout a typical day is as shown in Figure 11-3. The solid curve shows the storage temperature as sensed by S2. As illustrated in Figure 11-3, the collector temperature will begin to rise in the morning and

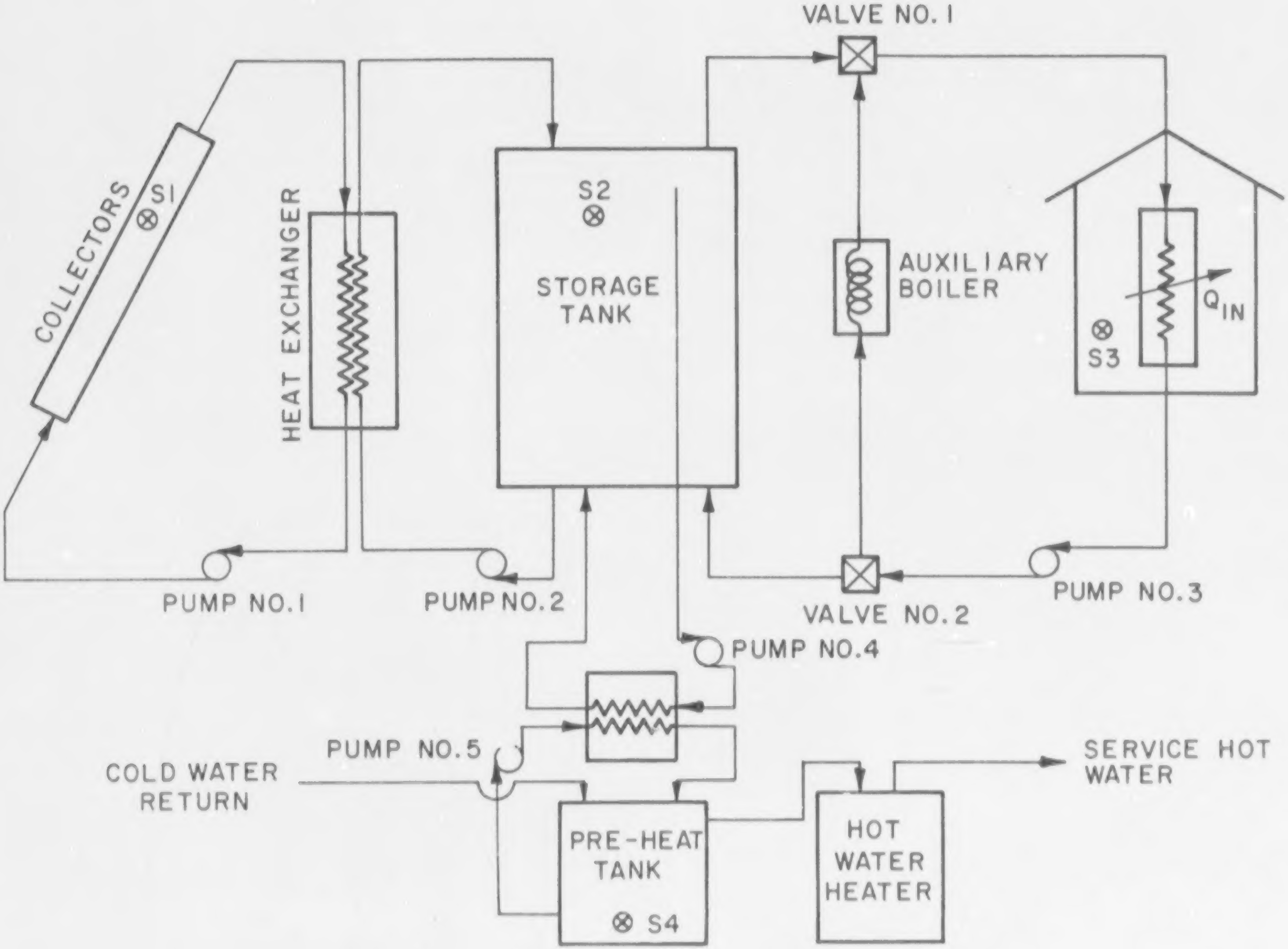

VALVE NO. 1
COLLECTORS
S1
HEAT EXCHANGER
S2
STORAGE TANK
AUXILIARY BOILER
S3
Q_{IN}
PUMP NO. 1
PUMP NO. 2
VALVE NO. 2
PUMP NO. 3
PUMP NO. 4
PUMP NO. 5
COLD WATER RETURN
SERVICE HOT WATER
PRE-HEAT TANK
S4
HOT WATER HEATER

Figure 11-2. Schematic Representation of a Typical Liquid System

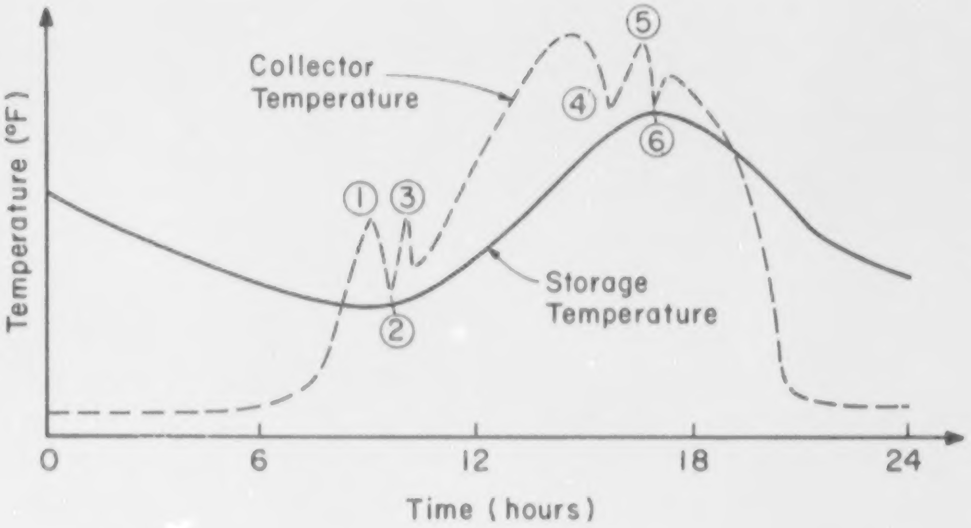


Figure 11-3. Typical Temperature Profiles

will exceed the storage temperature at some point. When the collector temperature exceeds the storage temperature by some preset amount, ΔT_{ON}, typically about 20°F, the collector/storage pumps will be turned on by the controller. This is indicated by point 1 in Figure 11-3. This will cause a surge of cooler fluid to circulate through the collectors, thereby lowering the collector temperature, as shown in the figure. If the decrease in collector temperature is great enough to cause the difference between the collector and storage temperatures to drop below another preset value, ΔT_{OFF}, typically about 3°F, the collector/storage pumps will be turned off, as indicated by point 2 in the figure. The temperature of the collector will again increase rather rapidly to point 3 at which time the collector/storage pumps will again be turned on. The amount of cycling of this type should be minimized in order to reduce wear on the pumps, pump motors, and relay contacts (if relays are used). If there is sufficient solar insolation, the collector temperature will continue to increase as illustrated in the figure, and the pumps will remain on until late in the afternoon. When the temperature differential has decreased again to ΔT_{OFF}, the collector/storage pumps will be turned off. This is represented by point 4 on the figure. This will cause the collector temperature to again increase due to the "no-flow" condition. If the temperature differential reaches ΔT_{ON}, the pumps will again be turned on (point 5 in the figure). This will lead to cooling of the collectors (point 6). The collector temperature will start to increase, but if the increase is not large enough, the pumps will remain off.

The sensors that are used in the sensor subsystem are typically thermistors, thermocouples, or transistors. The sensors that are provided with the controller should be used, since the controller is usually calibrated for a particular sensor. This is particularly true if thermistors are used, since the voltage output of the thermistor is a nonlinear function of temperature. Typical circuitry for a single function differential thermostat (controller) is shown in Figure 11-4 [see reference].

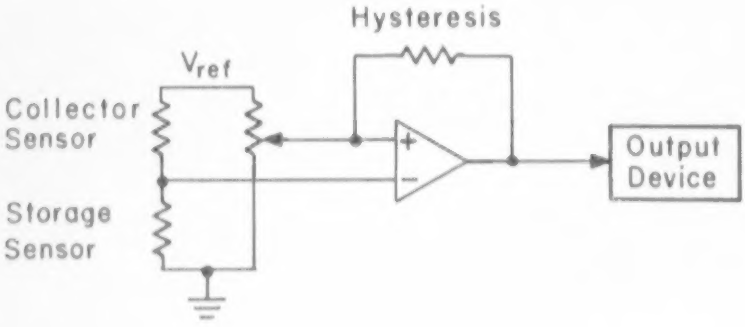


Figure 11-4. Typical Circuitry for a Differential Thermostat

The hysteresis is represented pictorially in Figure 11-5 and is realized physically by the feedback resistance shown in Figure 11-4.

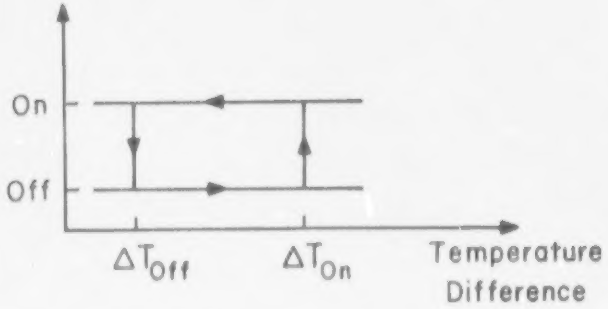


Figure 11-5. Pictorial Representation of Hysteresis in the Differential Thermostat

As shown in Figure 11-5, as the temperature difference increases and eventually reaches the value of ΔT_{ON}, the signal to the output device is such that the device is turned on. If the temperature difference decreases to the point where it is equal to ΔT_{OFF}, the OFF signal will be sent to the output device.

Ratio of Temperature Difference

If the temperature sensor for the collector is located where the sensor is rapidly cooled by the transport fluid, the result can be that the collector pumps will cycle on and off repeatedly. This cycling can also occur if the difference between the temperature to start and to stop the system is not properly selected. The ratio between the on to off temperature differences should be approximately five to seven. In the example given in the preceding paragraphs, the starting temperature difference was 20°F and the stopping temperature difference was 3°F. The ratio is slightly less than seven. A larger value for this ratio will reduce the total energy collected by the system, while a value smaller than five could cause cycling.

Freezing Protection

Some controllers are designed to incorporate an aquastat to compare the temperature of the transport medium with some preset temperature such as the freezing temperature of water. If the temperature of the fluid in the collector approaches this preset temperature, the pumps are automatically started to circulate the fluid or to heat the fluid from storage in order to prevent freezing. This is not a recommended protection measure against freezing, because if there is a power failure during cold weather, the pumps will not operate and the collectors can freeze. It is preferred to use an antifreeze solution in the collector loop.

Two-Speed Pump

A two-speed pump may be considered as a possible way to regulate the temperature rise in the collector to improve collection efficiency. By changing to a slower flow rate during periods of low solar insolation, the system will collect heat at useful temperatures, whereas with a high flow rate, the temperature of the fluid at the collector outlet would be low and the control would stop the collector pump. When the solar radiation intensity is high, the flow rate can be increased. The fluid temperature would be reduced because of greater flow, and the collector will operate more efficiently.

INSTALLATION OF CONTROL SYSTEM HARDWARE

The solar system controls consist of power relays which switch electric valves and pumps in the liquid system, or blowers and dampers in the air system, and auxiliary heating units in both systems, in response to temperatures or temperature differences. Controls for solar systems fundamentally serve the same functions as in conventional HVAC systems; however, there are more control functions in solar systems and also there are "interlocks" which prevent undesirable or hazardous sequences of operation.

A solar system supplier should provide the required control hardware, or at least specify it, along with explicit wiring instructions. Building a control system at the site should be avoided unless experience in this practice is available.

THERMOSTAT

A two-stage heat, indoor thermostat is recommended for residential solar heating systems, and a two-stage heat, one-stage cool type is recommended for solar heating and cooling systems. Variations will feature "on", "off", or "automatic" fan control to circulate the room air, and "heat", "cool", or "automatic" switches from heating to cooling or vice-versa to meet the need.

When cooling is required, the single-stage cooling provides indoor space temperature control. There is a deadband, which is a small range in temperature between start and stop signals given to the controller, which in turn controls the cooling system. The deadband for most thermostats is about 5°F. The heating operation is a bit more complex. Upon demand for heat, the first stage calls for the solar system to provide heat. If the building heat loss is greater than the solar system can provide, the temperature in the building will continue to drop to stage two and the auxiliary system will be called upon to provide heat. The auxiliary system can provide sufficient heat for the building by itself or in combination with the solar system to raise the temperature in the room to the upper temperature limit of stage one, which stops the heating system. The upper temperature deadband is nominally about 2°F.

The thermostat is the only control with which the occupant needs to be concerned. Once the occupant sets the winter comfort control level to, say, 68°F, and the summer comfort level to, say, 75°F (or other suitable temperatures), no further adjustment or temperature selection is needed for any other control in the heating and/or cooling system.

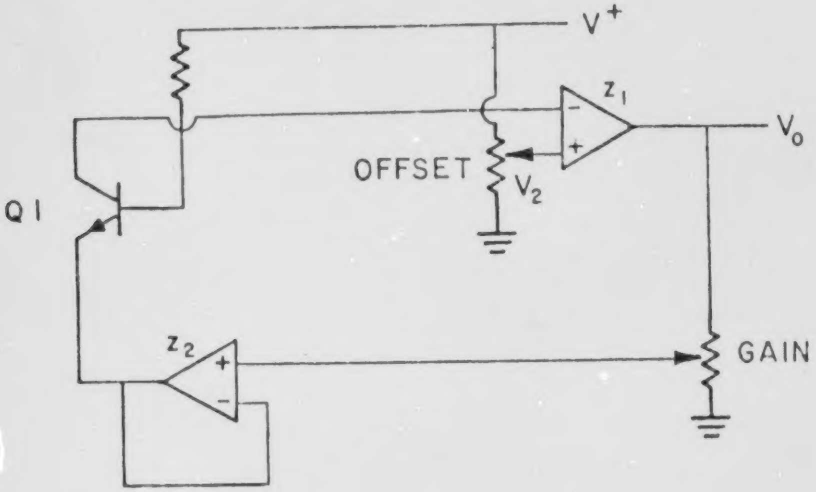
The thermostat should be installed following standard installation procedures. Instructions are normally supplied with the thermostat. Obviously, the thermostat should be located at a position such that the temperature at its point of location is representative of the average temperature within the enclosure.

TEMPERATURE SENSORS

Type

There are many types of temperature sensors that can be used in the control subsystem, such as thermocouples, thermistors, silicon transistors, bimetallic elements, and liquid or vapor expansion units. Liquid or vapor expansion units are seldom used because other temperature sensors are more durable and dependable. Thermocouples are frequently used for temperature measurement. However, they are not often used in controls because the voltage output is low, in the millivolt range, and without amplification the voltage is insufficient to be used in controls.

Thermistors and silicon transistors are used in the control subsystem because the voltage outputs from these sensors are in the 0 - 10 volt range and are high enough to serve the control functions. The voltage outputs from thermistors are nonlinear, and calibration circuitry must be provided for the nonlinearity. The voltage outputs from silicon transistors are linear in the normal operating temperature range of solar heating and cooling systems, and provide for simpler circuitry to control the system. A schematic diagram of the silicon transistor temperature sensor is shown in Figure 11-6.



$$V_o = \frac{V_2 - V_{be}}{G}$$

Figure 11-6. Silicon Transistor Circuit

Location

The locations of temperature sensors are not particularly critical, but there are some preferred locations. Temperature sensors are required to measure the air or liquid temperature as it exits from the collector, in the solar storage tank, or rock bed, and in the preheat water tank. The sensor in the conditioned space is the thermostat.

The sensor which measures the fluid temperature at the collector outlet can be located in the manifold which collects the fluid from the total array of collectors. It is preferred that the sensor be in contact with the fluid, but it is acceptable for the sensor to be in contact with the pipe, provided there is good thermal contact of the sensor with the pipe. If the sensor is attached to the outside of the outlet pipe, the sensor should be well insulated so that it does not lose the heat to the surroundings and register a low temperature. It is important to locate the sensor near the outlet so that it can register the fluid temperature when the sun is heating the collector but the fluid is not circulating. Sensors in the outlet manifold will register the increase in temperature,but the sensor located far from the manifold will not, and useful energy cannot then be collected. Wherever the sensor is located, the characteristics should be checked out when the system is put into operation.

The sensor in the storage tank should be located near the bottom third inside the tank. When there is no fluid circulation, the temperature at the top of the tank will be slightly higher than the bottom, but while the fluid is in circulation, the fluid in the tank is usually well mixed and the temperature will be uniform.

The location of the sensor in the preheat tank should be near the top one-third of the tank. If it were located near the bottom, the temperature at the top could be several degrees hotter. Also, when hot water is used in the household, cold water enters the preheat tank near the bottom. While the preheat tank would be thermally mixed when the pump is started, frequent cycling could result from the sensor registering locally cold water temperature. For an air system, the cycling is not particularly harmful because only one pump for the preheat cycle is involved. However, for the hydronic system, two pumps will be put into operation, and frequent cycling can be wasteful of electric energy. In both air and liquid systems, more heat would be lost than necessary from the pipes and heat exchangers because of frequent cycling.

The sensor in the pebble-bed should be located at the bottom (or outlet) end of storage. When heat is being stored, the bottom (or outlet) end of storage will determine if storage is "full".

CONTROL PANELS

Usually a central control panel is convenient to consolidate the circuits and relays that provide the control functions. The panel would house the relays and provide for some adjustment of the temperature limits. It is best to acquire a control panel from the solar equipment manufacturer as a prewired unit to serve the system. All that needs to be done with a prewired control panel is to connect the thermostat and other temperature sensors, motor, auxiliary unit, and the valves and damper controls to the proper terminals in the control panel. The manufacturer will provide the necessary instructions to make the connections. The power for the control panel will usually be household 115-volt, single-phase A.C. line power.

TYPICAL CONTROL SUBSYSTEM

CONTROL LOGIC, AIR SYSTEM

A sketch showing the sensor locations for an air heating solar system with a domestic hot water preheater and an evaporative cooler is shown in Figure 11-7. The temperature sensor, S1, is located in the duct at the top of the collector. It should be located at the top to register the temperature of the air as it is heated by the collector, which rises to the upper end of the collector even when the blower is not running. The temperature sensor S2 is located at the bottom of the rock-bed storage.

When the temperature at S1 is greater than at S2 by a preset amount, blower B1 is started and heat is delivered through storage. The temperature at sensor S2 will usually be the prevailing room air temperature because, during the previous night, the storage would have been used and room air enters the storage at the bottom.

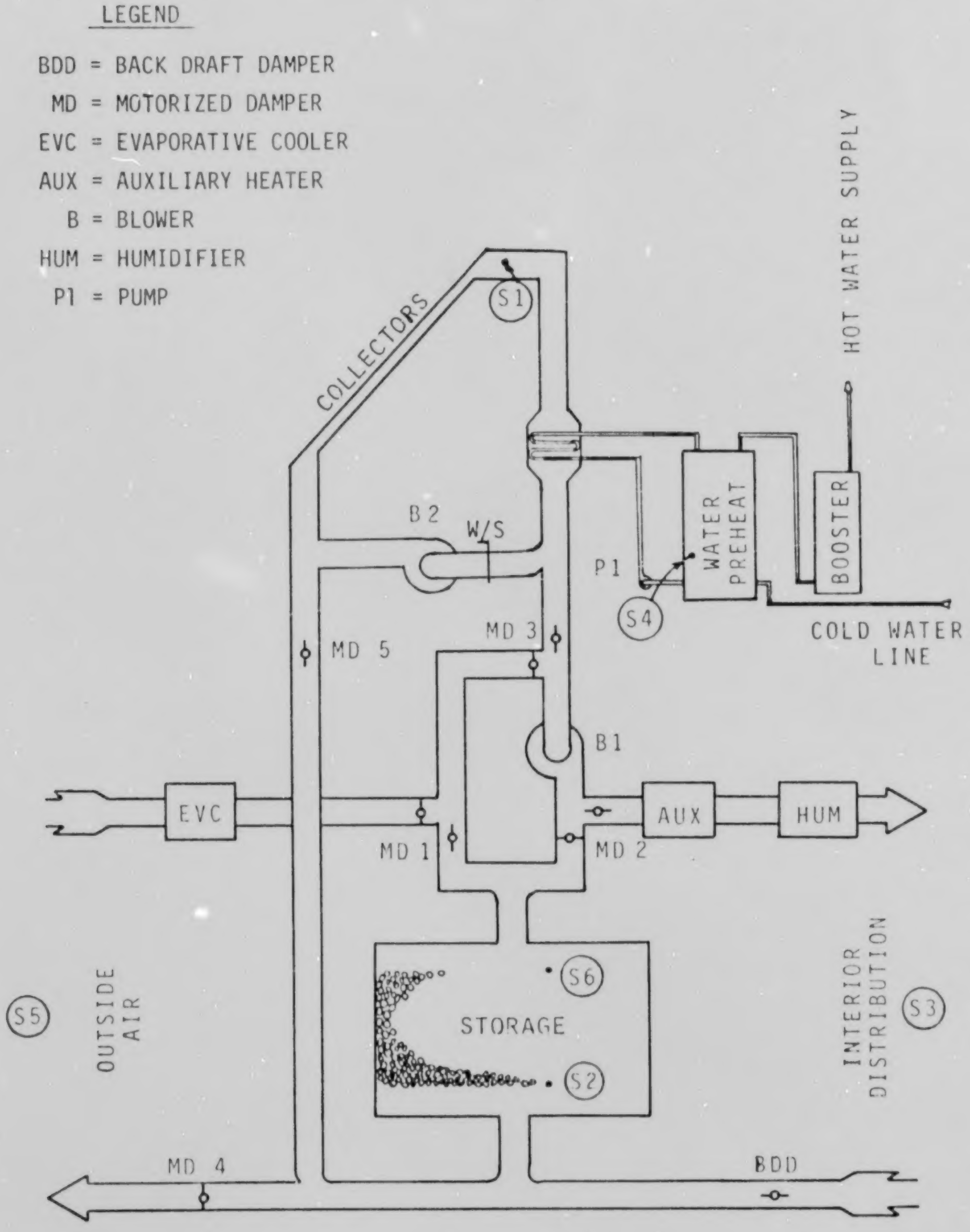

LEGEND
BDD = BACK DRAFT DAMPER
MD = MOTORIZED DAMPER
EVC = EVAPORATIVE COOLER
AUX = AUXILIARY HEATER
B = BLOWER
HUM = HUMIDIFIER
P1 = PUMP
HOT WATER SUPPLY
COLLECTORS
S1
B 2
W/S
WATER PREHEAT
BOOSTER
P1
S4
COLD WATER LINE
MD 5
MD 3
B1
EVC
AUX
HUM
MD 1
MD 2
S6
STORAGE
S2
S5
OUTSIDE AIR
INTERIOR DISTRIBUTION
S3
MD 4
BDD

Figure 11-7. Schematic of an Air System (Sensor Locations)

When the thermostat S3 places a demand for heat, the dampers MD2 and BDD respond and direct the flow into the room, provided that S1 is greater than the first-stage temperature setting of S3 by a preset amount. If the temperature in the room is not increased by the solar heat provided by the collectors directly to the rooms, the second-stage contact is made at S3. This could occur when solar energy is not available during the day and, of course, at night. The dampers MD3 and MD5 are actuated, the flow from the room is directed through storage, and the auxiliary furnace is then started. The damper MD5 is closed to offer more resistance along the reverse path through the collectors. The air circulates from the room, through storage, past the open damper MD1, and then through the auxiliary heater.

To provide heat to the service preheat water tank, the temperature at S4 is compared with S1. If S1 is greater than S4 by a preset amount, pump P1 is started and water is circulated through the cross-flow heat exchanger, unless S4 is greater than the temperature limiter which over-rides the S1-S4 command to prevent overheating the water. There is a prior over-ride command on pump P1, which is that the blower B1 must be on. When the temperature difference S1-S4 drops to the lower preset temperature difference, pump P1 stops.

The control logic described above for the air system serves to heat the house and provide for storage of heat. The preset lower temperature between S1, S2, and S4 can be the same as for the hydronic system.

To cool the rock bed during the night, a temperature sensor, S5, is needed outside the building. This sensor can be located at the inlet end of the duct leading to the evaporator cooler. When the temperature difference S2-S5 is less than a preset amount, outdoor air is drawn through the evaporator cooler and circulated through storage. The temperature that is desirable to register outdoors is the wet-bulb temperature, but this is not easily accomplished. Therefore, the dry-bulb temperature is used and the control reference temperature difference is set to allow for a prevailing wet-bulb temperature difference from the dry-bulb temperature. In dry climates this control strategy will function satisfactorily. There will be difficulties where the range of relative humidity can vary considerably at night.

During the day, the cool stage at thermostat S3 demands cooling. Blower B1 and the dampers are turned to circulate the room air through storage, provided the temperature difference S3-S6 is greater than a preset amount. The air circulation stops when the rooms cool and the contact at S3 is open.

For direct evaporative cooling of the rooms, an additional control circuitry is used which compares temperature difference S3-S6 to a preset value. That is, when cooling is no longer being provided from storage, direct evaporative cooling is provided by outside air through the EVC. Although room air could be circulated through the EVC for further cooling, it is not recommended because the humidity in the building can increase to an uncomfortable level.

CONTROL ACTUATORS

The pumps, blowers, valves, and dampers are referred to as the control actuators and produce the desired mechanical operation in response to the electrical control signals. Pumps and blowers are wired through manual switches from the control panel. The switch normally remains on and is a safety feature required in some electrical codes. The switches are to be placed near the motors and not at the control panel.

AUXILIARY HEAT CONTROL

The controls on a conventional boiler or forced air furnace must be changed for solar auxiliary purposes to be actuated in conjunction with the pumps and blowers in the solar system. The second stage thermostat is the main control to activate an auxiliary heater.

CONTROL SYSTEM CHECK-OUT

It is well to check the control system with a "dry" run through the full sequence of modes. The thermostat set points can usually be altered to fake the desired modes. This will assure that the system will "work" when it is first put into operation. Adjustments to the control system should be considered to effect the highest performance possible from the system. These adjustments include the setting of temperature differentials and deadbands.

REFERENCES

1. Peltzman, E.S., "Differential Thermostats for Solar Energy Systems", Rho Sigma, Inc., 15150 Raymer Street, Van Nuys, CA 91405.

TRAINING COURSE IN
THE PRACTICAL ASPECTS OF
SIZING, INSTALLATION, AND OPERATION OF SOLAR HEATING AND COOLING SYSTEMS
FOR
RESIDENTIAL BUILDINGS

MODULE 12

OPERATIONS LABORATORY

SOLAR ENERGY APPLICATIONS LABORATORY
COLORADO STATE UNIVERSITY
FORT COLLINS, COLORADO

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INTRODUCTION

The operations laboratory is an opportunity for the trainees to gain greater familiarity with hydronic and air solar systems and also for "hands on" experience with models of solar systems. The solar heating and cooling systems of the four CSU Solar Houses are to be examined in detail, measurements taken, and performance characteristics determined. The disassembled models of the solar systems are to be assembled by the trainees using the knowledge they have gained in the course.

OBJECTIVE

At the end of this module the trainee should be able to:

1. Explain the details of component arrangements in hydronic and air heating solar systems,
2. Obtain measurements from operating systems to understand the performance characteristics of solar hydronic and air systems.

INSTRUCTIONS

Four hours are devoted to this laboratory period. The class of trainees will be divided into four groups and each will be assigned an instructor for the entire period.

Group 1 - Group 1 will be formed by trainees who are interested in assembling the model hydronic system. The model system consists of collectors, storage, pumps and valves, controls, and a load. The model is to be assembled using the knowledge gained in the training course with minimal assistance from the instructor. The assembled system will be inspected by the instructor and improper assembly will receive comment.

Group 2 - Group 2 will be formed by trainees who are interested in assembling the model air system. The model consists of collectors, ducts, dampers, and a blower. A control unit is provided. The system is to be made operational and the completed assembly will be inspected.

Groups 3 and 4 - Groups 3 and 4 will include the balance of the class of trainees. The two groups will study the details of operating solar systems and obtain measurements. The experience gained from this exercise will develop a better understanding of system operating characteristics.

A schedule for the four groups during the laboratory period is presented in Table 12-1.

Table 12-1

Operations Laboratory Schedule

Event	Group			
	1	2	3	4
Model Assembly of Liquid System	1:00			
Model Assembly of Air System		1:00		
Inspection of Solar House III	3:00	4:00		
Inspection of Solar House IV	4:00	3:00		
Check Out of Solar House I			1:00	3:00
Check Out of Solar House II			3:00	1:00

OPERATIONS LABORATORY EVENTS

MODEL ASSEMBLY

An essential aspect of developing experience in the installation of solar heating and cooling systems is to assemble solar systems.

Although they are models of larger systems and only a few collectors are used, the experience of assembling the models will prove useful. The trainees should organize as a team and work together to complete the project.

The emphasis in the exercises is placed on locating the solar components in a proper arrangement to form a complete system. Flexible ducts and pipes are used for convenience in this model. The instructor will be available for questions, but the trainees should perform the assembly of all parts. After assembly, the instructor will provide comments and discuss alternative arrangements.

Liquid System Components

The components of the model liquid-heating solar system include:

1. Two solar collector modules
2. Collector support structure
3. Hot water storage tank
4. Two pumps
5. Simulated load
6. Valves, piping, and controls.

Assembly and Test

A schematic diagram of the model is shown in Figure 12-1. The trainees should study the diagram before beginning assembly of the model. It is possible that an alternative arrangement may be desired by participants in the group. Detailed instructions for assembly are not provided; rather the participants should decide the order of assembly.

After the model has been assembled, the system should be operated and the performance of the collector determined. For this purpose, temperatures should be measured at appropriate locations. The flow

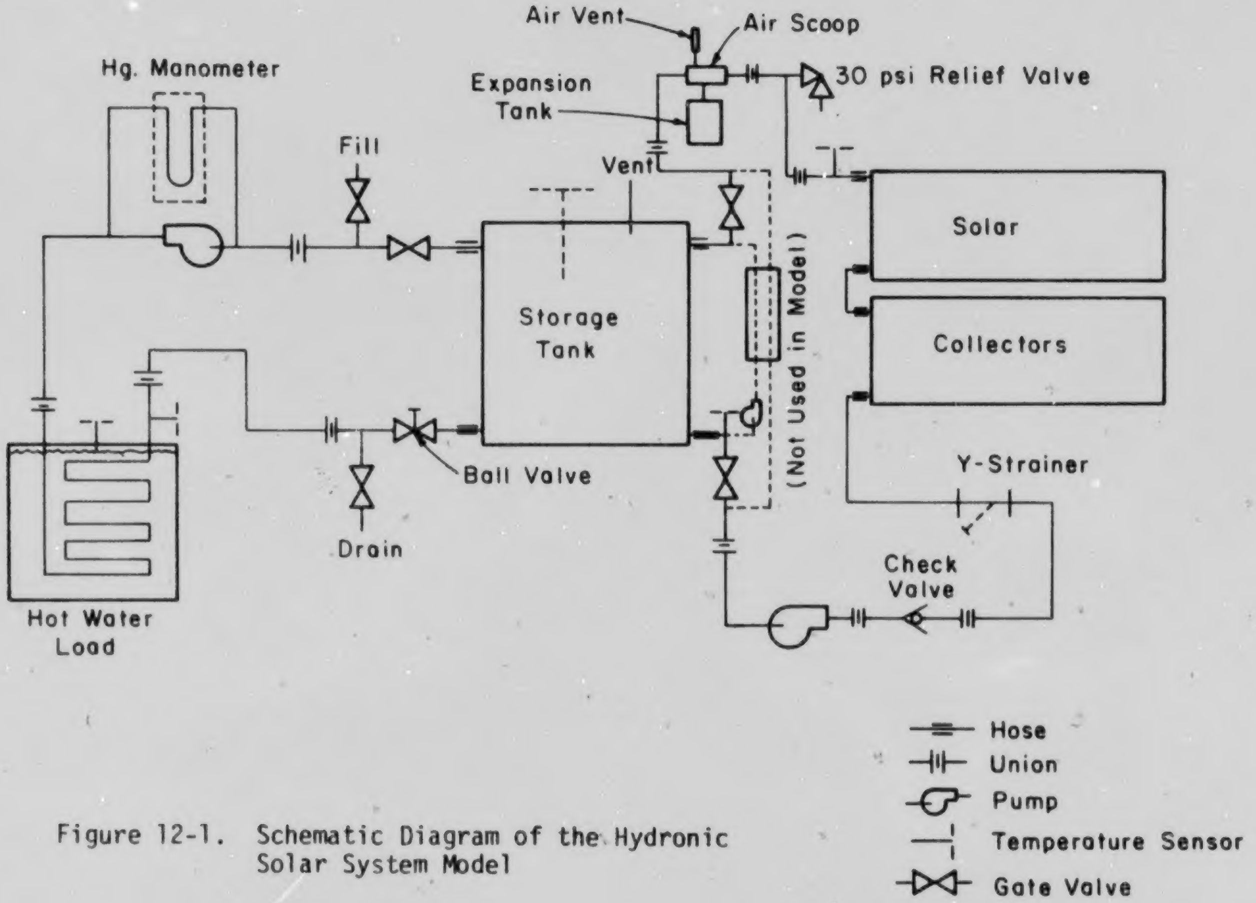

Air Vent
Air Scoop
30 psi Relief Valve
Hg. Manometer
Expansion Tank
Fill
Vent
Solar
Collectors
(Not Used in Model)
Storage Tank
Y-Strainer
Ball Valve
Drain
Check Valve
Hot Water Load
Hose
Union
Pump
Temperature Sensor
Gate Valve

Figure 12-1. Schematic Diagram of the Hydronic Solar System Model

rates through the collector pump can be determined by measuring the difference in pressure across the pump and referring to the discharge rating curve shown in Figure 12-2. The pumps have different capacity curves, depending upon pump speed. The solar radiation measured at one of the Solar Houses should be obtained for use in determining the collector performance.

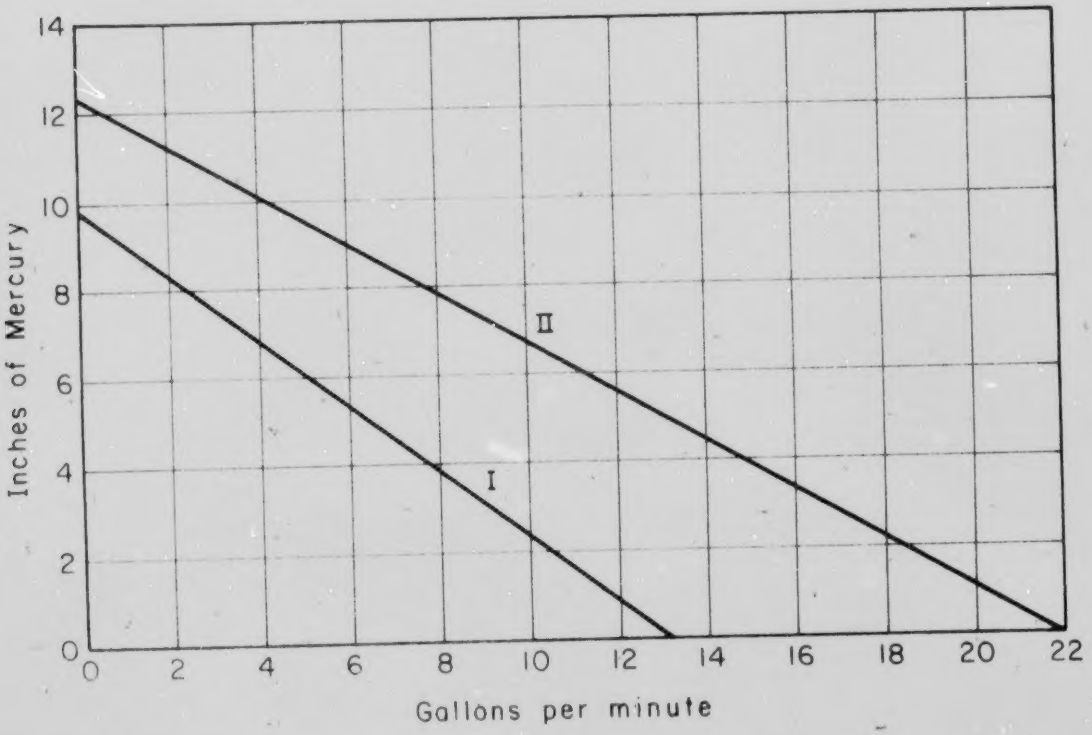


Figure 12-2. Grundfos Pump UPS-20-42 Full Flow Performance Curves

Air System Components

The components of the model air-heating solar system include:

1. Two solar collector modules
2. Collector support structure
3. Pebble-bed storage unit
4. Blowers, dampers, and flexible ducting

5. Controls
6. Simulated auxiliary furnace.

Assembly and Test

The recommended assembly of the air solar system model is shown schematically in Figure 12-3, and the control logic is shown in Figure 12-4. After assembling the components of the model, the system should be made operational. For this purpose, a wiring diagram for the model system is shown in Figure 12-5, and the terminal strip connections are shown in Figure 12-6. Four modes of operation are indicated in Figure 12-7.

The system should be tested and the performance of the collectors determined by measuring temperatures at appropriate locations. The flow rate for the blower will be provided by the instructor and the solar radiation can be obtained from the pyranometer readings on one of the solar houses.

SYSTEM INSPECTIONS

The trainees will be given approximately a 30-minute briefing of the solar systems in the houses and detailed locations of temperature sensors that are used for control and monitoring purposes. A detailed inspection of the system should be conducted by the trainees. Each should become fully familiar with the arrangements of different components of the systems.

SYSTEM CHECK-OUTS

Following the installation of any solar system or during a service call, it is recommended that the system be checked for proper performance.

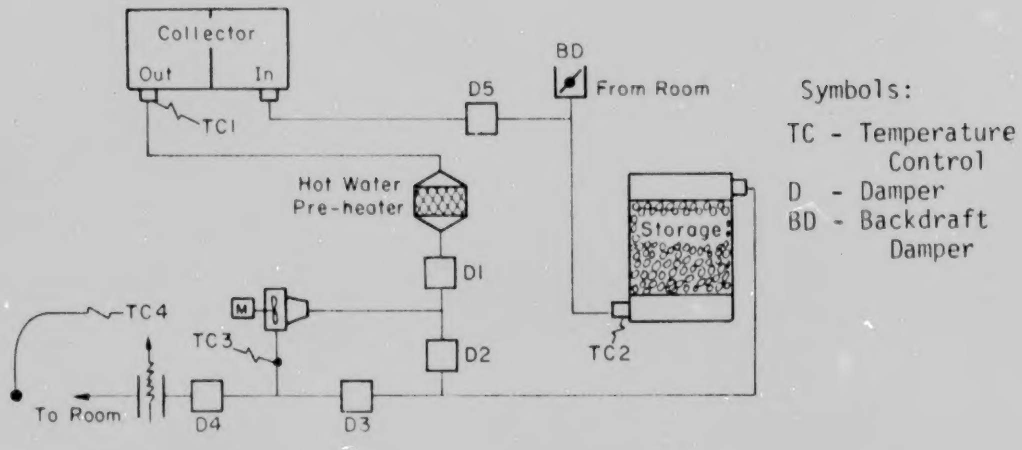

Collector
Out
In
TC1
D5
BD
From Room
Hot Water Pre-heater
Storage
D1
M
TC4
TC3
D2
TC2
To Room
D4
D3
Symbols:
TC - Temperature Control
D - Damper
BD - Backdraft Damper

Figure 12-3. Schematic Diagram of the Air Solar System Model

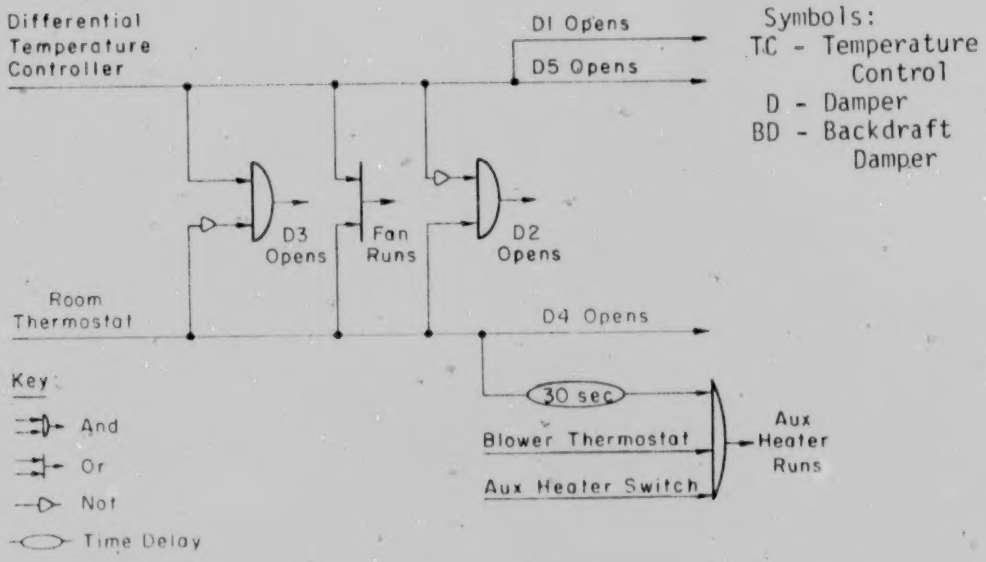

Differential Temperature Controller
D1 Opens
D5 Opens
D3 Opens
Fan Runs
D2 Opens
Room Thermostat
D4 Opens
30 sec
Blower Thermostat
Aux Heater Switch
Aux Heater Runs
Key:
And
Or
Not
Time Delay
Symbols:
TC - Temperature Control
D - Damper
BD - Backdraft Damper

Figure 12-4. Control Logic Diagram

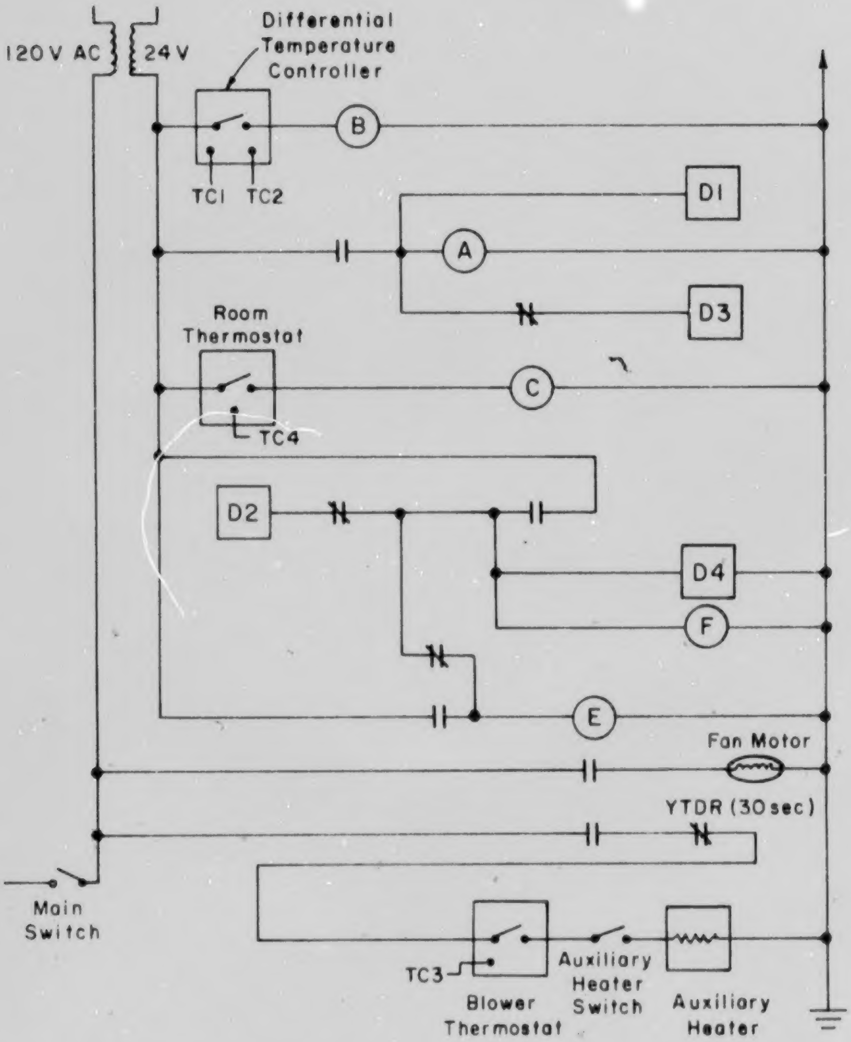

120 V AC
24 V
Differential Temperature Controller
B
TC1
TC2
D1
A
D3
Room Thermostat
C
TC4
D2
D4
F
E
Fan Motor
YTDR (30 sec)
Main Switch
TC3
Blower Thermostat
Auxiliary Heater Switch
Auxiliary Heater

Figure 12-5. Wiring Diagram for Model Air System

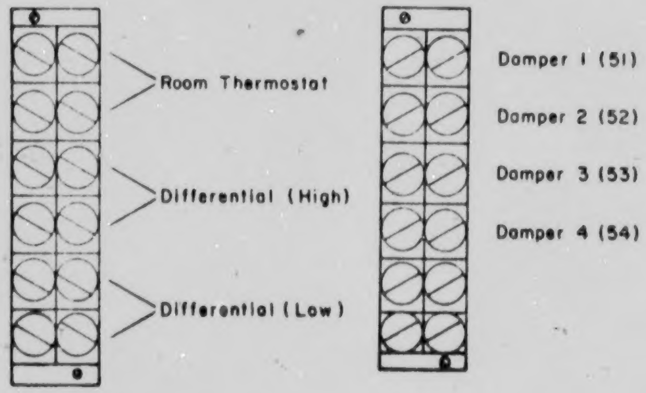
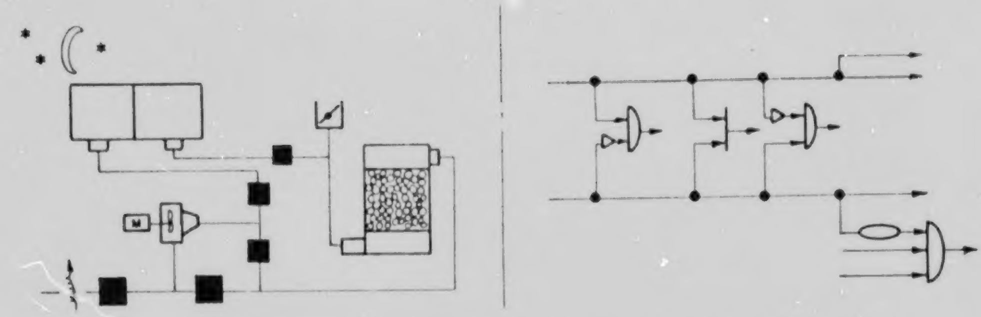
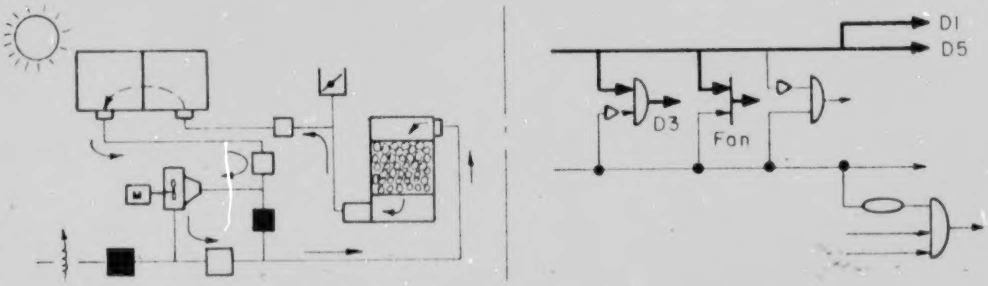

Room Thermostat
Differential (High)
Differential (Low)
Damper 1 (51)
Damper 2 (52)
Damper 3 (53)
Damper 4 (54)

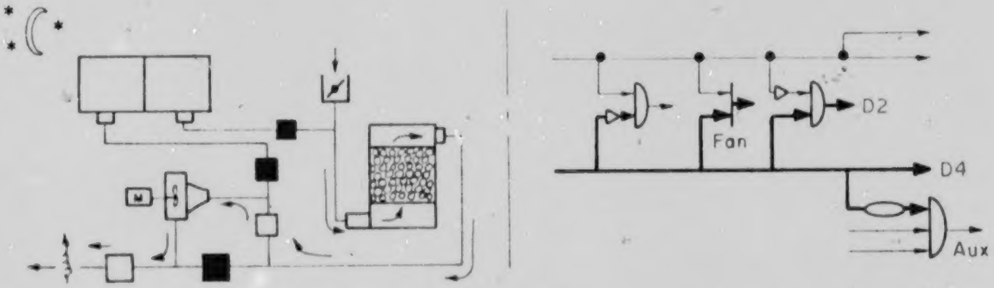
Figure 12-6. Terminal Strip Connections



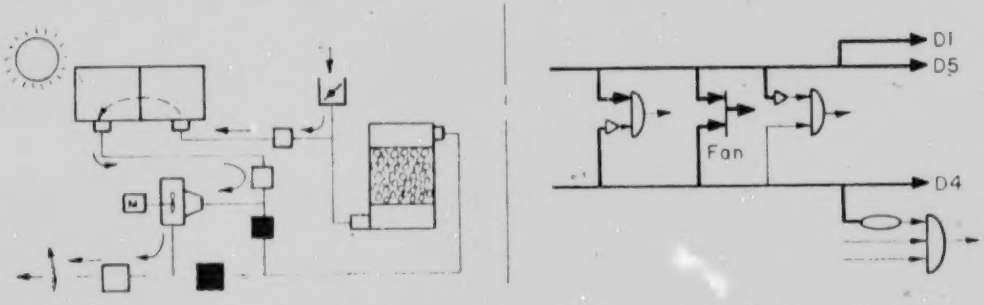
I) No Heat Available and No Heat Needed (System Off)



II) Heat is Available but No Heat is Needed (to Storage)


D2
Fan
D4
Aux

III) No Heat Available but Heat is Needed (from Storage)



IV) Heat is Available and Heat is Needed (Direct Heating)

Figure 12-7. Modes of Operation

If abnormal situations arise, the nature of the difficulty should be identified and the problem corrected.

An appropriate check list should be used to evaluate the performance of a solar system. The particular forms provided in this module will be discussed by the instructor. After the explanations, the trainees will endeavor to obtain a set of readings. Examples of a number of different data sets leading to different difficulties are provided. These examples will be discussed and the troubles will be identified.

EXAMPLE DATA
FROM A LIQUID-HEATING SOLAR SYSTEM
FOR
HEATING AND COOLING A
RESIDENTIAL BUILDING

Table 12-2. System Check List (Liquid), Example 1

	Readings		Remarks
COLLECTOR LOOP			
1. Inlet temperature to collector	196°F		
2. Outlet temperature from collector	198°F		
3. Collector temperature to heat exchanger/storage	197°F		
4. Collector temperature from heat exchanger/storage	196°F		
5. Collector loop flow rate	16.1 gpm		
6. Condition of collector			
a. Broken glass? none			
b. Dirt accumulation? slight			
*7. Surge tank level	low		
THERMAL STORAGE UNITS			
1. Storage tank temperature (top)	176°F		
2. Storage tank temperature (middle)	176°F		
3. Storage tank temperature (bottom)	172°F		
4. Storage tank temperature (below tank)	146°F		
*5. Cool storage supply to cooling unit	/	~~Cooling Off~~	
*6. Cool storage return from cooling unit	/		
HEATING/COOLING LOAD			
1. Storage/collector temperature to load	94°F		
2. Storage/collector temperature from load	88°F		
3. Load flow rate	0.5 gpm		
4. Solar/auxiliary valve position	solar		
5. Heating/cooling valve position	heating		
6. Return air temperature	70°F		
7. Supply air temperature	70°F		

*As appropriate to the particular system design

Table 12-2. System Check List (Liquid System), Example 1 (continued)

	Readings		Remarks
COOLING			
1. Cooling tower flow rate			
2. Cooling tower supply temperature			
3. Cooling tower return temperature			
4. Evaporator temperature			
5. Condenser temperature			
6. Vacuum (pressure)	OFF		
*7. Air flow across evaporator			
*8. Liquid flow across chiller			
DOMESTIC HOT WATER (DHW)			
1. DHW preheat temperature	128°F		
2. DHW auxiliary tank temperature	142°F		
3. DHW cold water main temperature (gas)	64°F		
4. Storage to preheat temperature	176°F		
5. Storage from preheat temperature	174°F		
6. Total water flow cumulative			

THERMOSTAT SETTINGS

House:	Heating	68°F	Cooling	72°F
Storage tank:	Heating	100°F	Cooling	170°F
Auxiliary:	Boiler	150°F	Hot Water	140°F

SYSTEM LINE UP FOR APPROPRIATE MODE

Remarks:

*As appropriate to the particular system design

Table 12-3. System Check List (Liquid), Example 2

	Readings		Remarks
COLLECTOR LOOP			
1. Inlet temperature to collector	208°F		
2. Outlet temperature from collector	212°F		
3. Collector temperature to heat exchanger/storage	212°F		
4. Collector temperature from heat exchanger/storage	208°F		
5. Collector loop flow rate	17.3 gpm		
6. Condition of collector			
a. Broken glass? Panel #2 - 1 lower glass			
b. Dirt accumulation? slight			
*7. Surge tank level	low		
THERMAL STORAGE UNITS			
1. Storage tank temperature (top)	209°F		
2. Storage tank temperature (middle)	209°F		
3. Storage tank temperature (bottom)	209°F		
4. Storage tank temperature (below tank)	180°F		
*5. Cool storage supply to cooling unit	209°F		
*6. Cool storage return from cooling unit	207°F		
HEATING/COOLING LOAD			
1. Storage/collector temperature to load	209°F		
2. Storage/collector temperature from load	207°F		
3. Load flow rate	0.2 gpm		
4. Solar/auxiliary valve position	solar		
5. Heating/cooling valve position	cooling		
6. Return air temperature	82°F		
7. Supply air temperature	83°F		

*As appropriate to the similar system design

Table 12-3. System Check List (Liquid System), Example 2 (continued)

	Readings		Remarks
COOLING			
1. Cooling tower flow rate	10.6 gpm		
2. Cooling tower supply temperature	72°F		
3. Cooling tower return temperature	73°F		
4. Evaporator temperature	70°F		
5. Condenser temperature	72°F		
6. Vacuum (pressure)	--		
*7. Air flow across evaporator	1550 cfm		
*8. Liquid flow across chiller	--		
DOMESTIC HOT WATER (DHW)			
1. DHW preheat temperature	135°F		
2. DHW auxiliary tank temperature	140°F		
3. DHW cold water main temperature	60°F		
4. Storage to preheat temperature	209°F		
5. Storage from preheat temperature	204°F		
6. Total water flow cumulative	--		

THERMOSTAT SETTINGS

House:	Heating	68°F	Cooling	72°F
Storage tank:	Heating	100°F	Cooling	70°F
Auxiliary:	Boiler	200°F	Hot Water	140°F

SYSTEM LINE UP FOR APPROPRIATE MODE

Remarks:

*As appropriate to the particular system design

Table 12-4. System Check List (Liquid), Example 3

	Readings	Remarks
COLLECTOR LOOP		
1. Inlet temperature to collector	141°F	
2. Outlet temperature from collector	148°F	
3. Collector temperature to heat exchanger/storage	147°F	
4. Collector temperature from heat exchanger/storage	142°F	
5. Collector loop flow rate	12.6 gpm	
6. Condition of collector		
a. Broken glass?	none	
b. Dirt accumulation?	considerable	
*7. Surge tank level	1/2 full	
THERMAL STORAGE UNITS		
1. Storage tank temperature (top)	153°F	
2. Storage tank temperature (middle)	153°F	
3. Storage tank temperature (bottom)	152°F	
4. Storage tank temperature (below tank)	112°F	
*5. Cool storage supply to cooling unit	NA	
*6. Cool storage return from cooling unit	NA	
HEATING/COOLING LOAD		
1. Storage/collector temperature to load	152°F	
2. Storage/collector temperature from load	141°F	
3. Load flow rate	10.3 gpm	
4. Solar/auxiliary valve position	Auxil	
5. Heating/cooling valve position	Cooling	
6. Return air temperature	76°F	
7. Supply air temperature	70°F	

*As appropriate to the particular system design

Table 12-4. System Check List (Liquid System), Example 3 (continued)

	Readings	Remarks
COOLING		
1. Cooling tower flow rate	10.1 gpm	
2. Cooling tower supply temperature	69°F	
3. Cooling tower return temperature	78°F	
4. Evaporator temperature	48°F	
5. Condenser temperature	75°F	
6. Vacuum (pressure)	--	
*7. Air flow across evaporator	1550 cfm	
*8. Liquid flow across chiller	--	
DOMESTIC HOT WATER (DHW)		
1. DHW preheat temperature	132°F	
2. DHW auxiliary tank temperature	140°F	
3. DHW cold water main temperature	60°F	
4. Storage to preheat temperature	150°F	
5. Storage from preheat temperature	142°F	
6. Total water flow cumulative	--	

THERMOSTAT SETTINGS

House:	Heating	68°F	Cooling	72°F
Storage tank:	Heating	100°F	Cooling	180°F
Auxiliary:	Boiler	160°F	Hot Water	140°F

SYSTEM LINE UP FOR APPROPRIATE MODE

Remarks:

*As appropriate to the particular system design

Table 12-5. System Check List (Liquid), Example 4

	Readings		Remarks
COLLECTOR LOOP			
1. Inlet temperature to collector	195°F		
2. Outlet temperature from collector	203°F		
3. Collector temperature to heat exchanger/storage	202°F		
4. Collector temperature from heat exchanger/storage	196°F		
5. Collector loop flow rate	17.3 gpm		
6. Condition of collector			
a. Broken glass? none			
b. Dirt accumulation? slight			
*7. Surge tank level	low		
THERMAL STORAGE UNITS			
1. Storage tank temperature (top)	201°F		
2. Storage tank temperature (middle)	200°F		
3. Storage tank temperature (bottom)	198°F		
4. Storage tank temperature (below tank)	156°F		
*5. Cool storage supply to cooling unit	--		
*6. Cool storage return from cooling unit	--		
HEATING/COOLING LOAD			
1. Storage/collector temperature to load	200°F		
2. Storage/collector temperature from load	191°F		
3. Load flow rate	11.2 gpm		
4. Solar/auxiliary valve position	solar		
5. Heating/cooling valve position	cooling		
6. Return air temperature	74°F		
7. Supply air temperature	68°F		

*As appropriate to the particular system design

Table 12-5. System Check List (Liquid System), Example 4 (continued)

	Readings		Remarks
COOLING			
1. Cooling tower flow rate	10.3 gpm		
2. Cooling tower supply temperature	72°F		
3. Cooling tower return temperature	79°F		
4. Evaporator temperature	42°F		
5. Condenser temperature	76°F		
6. Vacuum (pressure)	✓		
*7. Air flow across evaporator	1500 cfm		
*8. Liquid flow across chiller	--		
DOMESTIC HOT WATER (DHW)			
1. DHW preheat temperature	140°F		
2. DHW auxiliary tank temperature	140°F		
3. DHW cold water main temperature	65°F		
4. Storage to preheat temperature	86°F		
5. Storage from preheat temperature	91°F		
6. Total water flow cumulative	--		

THERMOSTAT SETTINGS

House:	Heating	68°F	Cooling	72°F
Storage tank:	Heating	150°F	Cooling	188°F
Auxiliary:	Boiler	190°F	Hot Water	140°F

SYSTEM LINE UP FOR APPROPRIATE MODE

Remarks:

*As appropriate to the particular system design

Table 12-6. System Check List (Liquid), Example 5

	Readings		Remarks
COLLECTOR LOOP			
1. Inlet temperature to collector	170°F		
2. Outlet temperature from collector	178°F		
3. Collector temperature to heat exchanger/storage	176°F		
4. Collector temperature from heat exchanger/storage	171°F		
5. Collector loop flow rate	16.2 gpm		
6. Condition of collector			
a. Broken glass? 2 panels (lower glass)			
b. Dirt accumulation? slight			
*7. Surge tank level	low		
THERMAL STORAGE UNITS			
1. Storage tank temperature (top)	175°F		
2. Storage tank temperature (middle)	175°F		
3. Storage tank temperature (bottom)	172°F		
4. Storage tank temperature (below tank)	140°F		
*5. Cool storage supply to cooling unit	--		
*6. Cool storage return from cooling unit	--		
HEATING/COOLING LOAD			
1. Storage/collector temperature to load	174°F		
2. Storage/collector temperature from load	173°F		
3. Load flow rate	10.3 gpm		
4. Solar/auxiliary valve position	solar		
5. Heating/cooling valve position	cooling		
6. Return air temperature	76°F		
7. Supply air temperature	76°F		

*As appropriate to the particular system design

Table 12-6. System Check List (Liquid System), Example 5 (continued)

	Readings	Remarks
COOLING		
1. Cooling tower flow rate	10.6 gpm	
2. Cooling tower supply temperature	80°F	
3. Cooling tower return temperature	82°F	
4. Evaporator temperature	67°F	
5. Condenser temperature	82°F	
6. Vacuum (pressure)	✓	
*7. Air flow across evaporator	1600 cfm	
*8. Liquid flow across chiller	--	
DOMESTIC HOT WATER (DHW)		
1. DHW preheat temperature	136°F	
2. DHW auxiliary tank temperature	140°F	
3. DHW cold water main temperature	70°F	
4. Storage to preheat temperature	135°F	
5. Storage from preheat temperature	128°F	
6. Total water flow cumulative	✓	

THERMOSTAT SETTINGS

House:	Heating	68°F	Cooling	70°F
Storage tank:	Heating	100°F	Cooling	170°F
Auxiliary:	Boiler	180°F	Hot Water	140°F

SYSTEM LINE UP FOR APPROPRIATE MODE

Remarks:

*As appropriate to the particular system design

EXAMPLE DATA
FROM AN AIR-HEATING SOLAR SYSTEM
FOR
HEATING A RESIDENTIAL BUILDING

Table 12-7. System Check List (Air), Example 1

	Readings	Remarks
COLLECTOR LOOP		
1. Inlet temperature to collector	76°F	
2. Outlet temperature from collector	151°F	
3. Air temp. before heat exchanger	137°F	
4. Air temp. after heat exchanger	129°F	
5. Collector loop air flow rate	1510 cfm	
6. Conditions of collector		
a. Broken glass? Panel #1, lower cover		
b. Dirt accumulation? None		
THERMAL STORAGE UNITS		
1. Inlet temperature	125°F	
2. Storage unit temperature (top)	124°F	
3. Storage unit temperature (middle)	122°F	
4. Storage unit temperature (bottom)	81°F	
5. Outlet temperature	78°F	
HEATING/COOLING LOAD		
1. Room air supply temperature	126°F	
2. Room air return temperature	73°F	
3. Air flow rate to rooms	1510 cfm	
DOMESTIC HOT WATER (DHW)		
1. DHW preheat temperature	132°F	
2. DHW auxiliary tank temp. setting	142°F	
3. DHW cold water main temperature	70°F	
4. Air/liquid exchanger to preheat temp	136°F	
5. Air/liquid exchanger from preheat temp	130°F	
6. Water flow rate through heat exchanger	--	

THERMOSTAT SETTINGS

House: Heating 72°F

Storage Unit: Heating 100°F

Auxiliary: Boiler 160°F Hot Water 140°F

Table 12-8. System Check List (Air), Example 2

	Readings	Remarks
COLLECTOR LOOP		
1. Inlet temperature to collector	75°F	
2. Outlet temperature from collector	175°F	
3. Air temp. before heat exchanger	163°F	
4. Air temp. after heat exchanger	147°F	
5. Collector loop air flow rate	780 cfm	
6. Conditions of collector		
a. Broken glass? None		
b. Dirt accumulation? Slight		
THERMAL STORAGE UNITS		
1. Inlet temperature	144°F	
2. Storage unit temperature (top)	143°F	
3. Storage unit temperature (middle)	79°F	
4. Storage unit temperature (bottom)	76°F	
5. Outlet temperature	72°F	
HEATING/COOLING LOAD		
1. Room air supply temperature	off	
2. Room air return temperature	off	
3. Air flow rate to rooms	off	
DOMESTIC HOT WATER (DHW)		
1. DHW preheat temperature	96°F	
2. DHW auxiliary tank temp. setting	144°F	
3. DHW cold water main temperature	62°F	
4. Air/liquid exchanger to preheat temp	133°F	
5. Air/liquid exchanger from preheat temp	95°F	
6. Water flow rate through heat exchanger	--	

THERMOSTAT SETTINGS

House: Heating 70°F

Storage Unit: Heating 100°F

Auxiliary: Boiler 150°F Hot Water 140°F

Table 12-9. System Check List (Air), Example 3

	Readings	Remarks
COLLECTOR LOOP		
1. Inlet temperature to collector	41°F	
2. Outlet temperature from collector	40°F	
3. Air temp. before heat exchanger	52°F	
4. Air temp. after heat exchanger	51°F	
5. Collector loop air flow rate	--	
6. Conditions of collector		
a. Broken glass? Night		
b. Dirt accumulation? Night		
THERMAL STORAGE UNITS		
1. Inlet temperature	153°F	
2. Storage unit temperature (top)	151°F	
3. Storage unit temperature (middle)	148°F	
4. Storage unit temperature (bottom)	83°F	
5. Outlet temperature	80°F	
HEATING/COOLING LOAD		
1. Room air supply temperature	150°F	
2. Room air return temperature	68°F	
3. Air flow rate to rooms	1430 cfm	
DOMESTIC HOT WATER (DHW)		
1. DHW preheat temperature	126°F	
2. DHW auxiliary tank temp. setting	142°F	
3. DHW cold water main temperature	63°F	
4. Air/liquid exchanger to preheat temp	76°F	
5. Air/liquid exchanger from preheat temp	75°F	
6. Water flow rate through heat exchanger	--	

THERMOSTAT SETTINGS

House: Heating 68°F

Storage Unit: Heating 100°F

Auxiliary: Boiler 150°F Hot Water 145°F

BLANK CHECK LIST FORMS

Operations System Check List

(Liquid System)

	Readings		Remarks
COLLECTOR LOOP			
1. Inlet temperature to collector			
2. Outlet temperature from collector			
3. Collector temperature to heat exchanger/storage			
4. Collector temperature from heat exchanger/storage			
5. Collector loop flow rate			
6. Condition of collector			
a. Broken glass? ____________			
b. Dirt accumulation? ____________			
*7. Surge tank level			
THERMAL STORAGE UNITS			
1. Storage tank temperature (top)			
2. Storage tank temperature (middle)			
3. Storage tank temperature (bottom)			
4. Storage tank temperature (below tank)			
*5. Cool storage supply to cooling unit			
*6. Cool storage return from cooling unit			
HEATING/COOLING LOAD			
1. Storage/collector temperature to load			
2. Storage/collector temperature from load			
3. Load flow rate			
4. Solar/auxiliary valve position			
5. Heating/cooling valve position			
6. Return air temperature			
7. Supply air temperature			

*As appropriate to the particular system design

Operations System Check List (continued)

	Readings		Remarks
COOLING			
1. Cooling tower flow rate	______	______	______________________________
2. Cooling tower supply temperature	______	______	______________________________
3. Cooling tower return temperature	______	______	______________________________
4. Evaporator temperature	______	______	______________________________
5. Condenser temperature	______	______	______________________________
6. Vacuum (pressure)	______	______	______________________________
*7. Air flow across evaporator	______	______	______________________________
*8. Liquid flow across chiller	______	______	______________________________
DOMESTIC HOT WATER (DHW)			
1. DHW preheat temperature	______	______	______________________________
2. DHW auxiliary tank temperature	______	______	______________________________
3. DHW cold water main temperature	______	______	______________________________
4. Storage to preheat temperature	______	______	______________________________
5. Storage from preheat temperature	______	______	______________________________
6. Total water flow cumulative	______	______	______________________________

THERMOSTAT SETTINGS

House: Heating ________ Cooling ________
Storage tank: Heating ________ Cooling ________
Auxiliary: Boiler ________ Hot Water ________

SYSTEM LINE UP FOR APPROPRIATE MODE

Remarks:
____
____
____
____
____

*As appropriate to the particular system design

Operations System Check List (Air System)

COLLECTOR LOOP

	Readings	Remarks
1. Inlet temperature to collector	______	____________________
2. Outlet temperature from collector	______	____________________
3. Air temp. before heat exchanger	______	____________________
4. Air temp. after heat exchanger	______	____________________
5. Collector loop air flow rate	______	____________________
6. Conditions of collector		
a. Broken glass?______________		____________________
b. Dirt accumulation?__________		____________________

THERMAL STORAGE UNITS

	Readings	Remarks
1. Inlet temperature	______	____________________
2. Storage unit temperature (top)	______	____________________
3. Storage unit temperature (middle)	______	____________________
4. Storage unit temperature (bottom)	______	____________________
5. Outlet temperature	______	____________________

HEATING/COOLING LOAD

	Readings	Remarks
1. Room air supply temperature	______	____________________
2. Room air return temperature	______	____________________
3. Air flow rate to rooms	______	____________________

DOMESTIC HOT WATER (DHW)

	Readings	Remarks
1. DHW preheat temperature	______	____________________
2. DHW auxiliary tank temp. setting	______	____________________
3. DHW cold water main temperature	______	____________________
4. Air/liquid exchanger to preheat temp	______	____________________
5. Air/liquid exchanger from preheat temp	______	____________________
6. Water flow rate through heat exchanger	______	____________________

THERMOSTAT SETTINGS

House: Heating __________

Storage Unit: Heating __________

Auxiliary: Boiler __________ Hot Water _________

Operations System Check List

(Liquid System)

	Readings		Remarks
COLLECTOR LOOP			
1. Inlet temperature to collector			
2. Outlet temperature from collector			
3. Collector temperature to heat exchanger/storage			
4. Collector temperature from heat exchanger/storage			
5. Collector loop flow rate			
6. Condition of collector			
a. Broken glass?			
b. Dirt accumulation?			
*7. Surge tank level			
THERMAL STORAGE UNITS			
1. Storage tank temperature (top)			
2. Storage tank temperature (middle)			
3. Storage tank temperature (bottom)			
4. Storage tank temperature (below tank)			
*5. Cool storage supply to cooling unit			
*6. Cool storage return from cooling unit			
HEATING/COOLING LOAD			
1. Storage/collector temperature to load			
2. Storage/collector temperature from load			
3. Load flow rate			
4. Solar/auxiliary valve position			
5. Heating/cooling valve position			
6. Return air temperature			
7. Supply air temperature			

*As appropriate to the particular system design

Operations System Check List (continued)

	Readings		Remarks
COOLING			
1. Cooling tower flow rate	____	____	____________
2. Cooling tower supply temperature	____	____	____________
3. Cooling tower return temperature	____	____	____________
4. Evaporator temperature	____	____	____________
5. Condenser temperature	____	____	____________
6. Vacuum (pressure)	____	____	____________
*7. Air flow across evaporator	____	____	____________
*8. Liquid flow across chiller	____	____	____________
DOMESTIC HOT WATER (DHW)			
1. DHW preheat temperature	____	____	____________
2. DHW auxiliary tank temperature	____	____	____________
3. DHW cold water main temperature	____	____	____________
4. Storage to preheat temperature	____	____	____________
5. Storage from preheat temperature	____	____	____________
6. Total water flow cumulative	____	____	____________

THERMOSTAT SETTINGS

House:	Heating	________	Cooling	________
Storage tank:	Heating	________	Cooling	________
Auxiliary:	Boiler	________	Hot Water	________

SYSTEM LINE UP FOR APPROPRIATE MODE

Remarks: ____

____

____

____

____

*As appropriate to the particular system design

Operations System Check List (Air System)

	Readings	Remarks
COLLECTOR LOOP		
1. Inlet temperature to collector	______	____________________
2. Outlet temperature from collector	______	____________________
3. Air temp. before heat exchanger	______	____________________
4. Air temp. after heat exchanger	______	____________________
5. Collector loop air flow rate	______	____________________
6. Conditions of collector		
a. Broken glass?______________		____________________
b. Dirt accumulation?__________		____________________
THERMAL STORAGE UNITS		
1. Inlet temperature	______	____________________
2. Storage unit temperature (top)	______	____________________
3. Storage unit temperature (middle)	______	____________________
4. Storage unit temperature (bottom)	______	____________________
5. Outlet temperature	______	____________________
HEATING/COOLING LOAD		
1. Room air supply temperature	______	____________________
2. Room air return temperature	______	____________________
3. Air flow rate to rooms	______	____________________
DOMESTIC HOT WATER (DHW)		
1. DHW preheat temperature	______	____________________
2. DHW auxiliary tank temp. setting	______	____________________
3. DHW cold water main temperature	______	____________________
4. Air/liquid exchanger to preheat temp	______	____________________
5. Air/liquid exchanger from preheat temp	______	____________________
6. Water flow rate through heat exchanger	______	____________________

THERMOSTAT SETTINGS

House: Heating _________

Storage Unit: Heating _________

Auxiliary: Boiler _________ Hot Water _________

TRAINING COURSE IN
THE PRACTICAL ASPECTS OF
SIZING, INSTALLATION, AND OPERATION OF SOLAR HEATING AND COOLING SYSTEMS
FOR
RESIDENTIAL BUILDINGS

MODULE 13

HEATING LOAD CALCULATIONS

SOLAR ENERGY APPLICATIONS LABORATORY
COLORADO STATE UNIVERSITY
FORT COLLINS, COLORADO

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GLOSSARY

Design Temperature - Lowest temperature encountered in the locality

Degree Days (DD) - The temperature difference between a reference temperature, 65°F, and the average of the high and low temperature during a day (°F-days)

Example:

high temperature = 30°F

low temperature = -10°F

$$\text{average temperature} = \frac{30 + (-10)}{2} = 10°\text{F}$$

Degree Days = 65 - 10 = 55°F-days

Design Temperature Difference (DTD) - The difference between the indoor design temperature and the outdoor design temperature used to calculate heat losses from buildings

Design Heat Loss Rate - The heat loss rate (Btu/hr) from a building based upon the Design Temperature Difference

Space Heating Load - Design Heat Loss Rate divided by the Design Temperature Difference and the quotient multiplied by 24 hours (Btu/DD)

Average Heating Load - Space Heating Load multiplied by Degree Days for the day, month, or year (Btu)

INTRODUCTION

There has not been much need in the past to make detailed heat load calculations for residential buildings because the HVAC contractor "knew", from his experience, the size of furnace that a particular building would require in a given area. Furnaces have been characteristically oversized for residential buildings.

Heating loads for buildings with solar systems should be calculated because the size of the solar system, and estimate of the fraction of the annual heating load which a solar system can supply, depends upon the annual heating load of the building. Furthermore, the determination of the economic viability of a solar system is dependent upon the size of the solar system and the annual heating load.

OBJECTIVE

The objective of the trainee is to be able to calculate the design heat load (maximum Btu per hour requirement), average heating loads for January, and the average annual heating load for a particular building.

HEAT LOAD FACTORS

The heat loss from a building is calculated on the basis of the wall and ceiling areas of the building, the heat loss coefficients for heat transmission through the walls and ceiling, the difference between the indoor and outdoor temperature, and the infiltration of cold air into the building.

RESISTANCE TO HEAT FLOW (R) AND COEFFICIENT OF HEAT TRANSMISSION (U)

Values of the resistance to heat flow, R, and the coefficient of heat transmission, U, vary considerably for different materials. The resistance, R, has units of $(hr)(ft^2)$(°F temperature difference)/Btu and is the reciprocal of heat conductance, C. For a given material and thickness,

$$R = 1/C$$

where C is the conductance in $Btu/(hr)(ft^2)(°F)$.

The thermal conductivity, k, is the rate of heat conduction through a unit area of surface for a unit thickness of material. The units of k in this manual are $(Btu)(in.)/(hr)(ft^2)(°F)$. If k is known, the resistance may be calculated from

$$R = (1/k) \times (\text{thickness of the material}).$$

Values of R are additive, and the coefficient of heat transmission, U, is the reciprocal of the sum of the R values:

$$U = \frac{1}{R_1 + R_2 + R_3 + \ldots} = \frac{1}{\Sigma R} \quad \frac{\text{Btu}}{(\text{hr})(\text{ft}^2)(°\text{F temperature difference})}$$

Some values of R, U, and 1/k are given in Table 13-1.

HEAT LOSS RATE

The rate of heat loss, h, in Btu/hr through a surface of area, A, with a temperature difference across the two sides of the surface of ΔT, is:

$$h = U A \Delta T \qquad [13\text{-}1]$$

where A is in square feet and

ΔT is in degrees Fahrenheit

Table 13-1

Values of R, U, and 1/k for Some Structural and Finish Materials, Glass, Doors, Insulation, Air Spaces, and Surface Air Films †

Materials			1/k	R	U
Wood bevel siding, .5 x 8, lapped				0.81	
Wood siding shingles, 16" x 7.5" exposure				0.87	
Asbestos-cement shingles				0.21	
Stucco			0.20		
Building paper				0.06	
1/2"nail-base insulation board sheathing				1.14	
Insulation board sheathing, regular density			2.63		
Plywood			1.24		
1/4" hardboard				0.18	
Softwood board			1.25		
Concrete blocks, 3 oval cores					
	Cinder Aggregate	4" thick		1.11	
		12" thick		1.89	
		8" thick		1.72	
	Sand and gravel aggregate, 8" thick			1.11	
	Lightweight aggregate, 8" thick			2.00	
Concrete blocks, 2 rectangular cores					
	Sand and gravel aggregate, 8" thick			1.04	
	Lightweight aggregate, 8" thick			2.18	
Common brick			0.20		
Face brick			0.11		
Sand-and-gravel concrete			0.08		
Gypsumboard (plasterboard)			0.90		
.5" lightweight-aggregate gypsum plaster				0.32	
25/32" hardwood finish flooring				0.68	
Asphalt, linoleum, vinyl, or rubber floor tile				0.05	
Carpet and fibrous pad				2.08	
Carpet and foam rubber pad				1.23	
Asphalt roof shingles				0.44	
Wood roof shingles				0.94	
3/8" built-up roof				0.33	
Basement floor below grade					0.06
Glass					
	Single				1.13
	Double	1/4" air space			0.65
		1/2" air space			0.58
	Triple	1/4" air spaces			0.47
		1/2" air spaces			0.36
	Storm windows (1-4" air space)				0.56

---

† From ASHRAE Handbook of Fundamentals

Table 13-1 (continued)†

Solid Wood Slab Door U Values:	No Storm Door	Storm Door Wood	Storm Door Metal
1.00" thick	0.64	0.30	0.39
1.25" thick	0.55	0.28	0.34
1.50" thick	0.49	0.27	0.33
2.20" thick	0.43	0.24	0.29

Insulation:	1/k	R	U
0" thick		0	
2.0 - 2.75" thick	3.58	7	
3.0 - 3.5" thick	3.58	11	
3.5 - 3.625" thick	3.58	13	
5.25 - 6.5" thick	3.58	19	
6.0 - 7.0" thick	3.58	22	

Approximate U values for ceiling, walls, and floors (other than concrete slabs) with given insulation (R value). If heating unit is in the basement and if ducts or pipes are uninsulated, no floor loss calculation is necessary. For floors over unheated basements, use 1/3 of the approximate U value given or 1/3 of the calculated U value. For floors over unvented crawlspaces with insulated crawlspace walls, use 1/2 of the approximate U value given or 1/2 of the calculated U value. For floors over vented crawl spaces or other open spaces, use the approximate U value given or the calculated U value. Use of the approximate U values given here for a given R value will usually result in a higher heat load than will actually be the case.

R	U
0	0.28*
7	0.11
11	0.08
13	0.07
19	0.05
22	0.045

Concrete Slab Floors: Use linear feet of exposed length of slab edge in place of A: h = U (lin. ft) ΔT

	1/k	R	U
1" x 24" insulation			0.21
1" x 12" insulation			0.46
No insulation			0.81

			1/k	R	U
Air Spaces (3-4")	Heat Flow Up	Non-reflective		0.87	
		Reflective, 1 surface**		2.23	
	Heat Flow Down or Horizontal	Non-reflective		1.01	
		Reflective, 1 surface**		3.50	
Surface Air Films	Heat Flow Up	Non-reflective		0.61	
		Reflective		1.32	
	Heat Flow Down	Non-reflective		0.92	
		Reflective		4.55	
	Heat Flow Horizontal	Through vertical surface, non-reflective		0.68	
	Outside (15 mph wind)			0.17	

* When R = 0, actual U values may range from 0.2 to 0.5

** The addition of a second reflective surface facing the first reflective surface increases the thermal resistance values of an air space only 4 to 7%.

† From ASHRAE Handbook of Fundamentals

The temperature difference that is used to calculate the heat loss rate is the difference between the room temperature, T_R, and the design outdoor temperature, T_o:

$$\Delta T = T_R - T_o \qquad [13\text{-}2]$$

The room temperature is nominally 70 degrees and the design outdoor temperatures are listed in Table 13-2 for many cities in the United States. Also listed on the table are monthly and total annual heating degree days, which will be utilized in the heating load calculations. Table 13-2 is located at the end of this module for the convenience of the user.

CONCRETE SLABS ON GRADE

The heat loss rate from concrete slab on grade is calculated on the basis of exposed edge length rather than on floor area. The heat loss rate is:

$$h = U\ (\text{linear feet of exposed slab area})\ \Delta T \qquad [13\text{-}3]$$

where ΔT is the difference between indoor and average outdoor temperature in degrees Fahrenheit.

The U values are listed in Table 13-1.

BASEMENTS

Basement floors below grade have a heat loss rate of about $\dfrac{1\ \text{Btu/hr}}{\text{ft}^2\ \text{of floor area}}$. In Table 13-1, for basement walls below grade, $U = 0.06\ \text{Btu/(hr)(ft}^2\text{)(°F)}$. The temperature difference is the indoor temperature minus the ground temperature, and the ground temperature is often assumed to be the same as ground water temperature and, in most regions, can be assumed to be about 45°F in winter.

DUCT HEAT LOSS

When a duct is installed within the insulated envelope, there is no heat loss from the building. If the ducts are located in crawlspaces or outside the building envelope, about 10 percent of the heat carried by the duct will be lost.

INFILTRATION HEAT LOSS

The cold air that enters a building through open doors, windows and cracks around doors and windows constitutes a heat loss because the cold air displaces the warm room air and the cold air must be heated to room air temperature. The infiltration heat loss rate can be computed from:

$$h = 0.018\,V\,(\Delta T) \qquad [13\text{-}4]$$

where V is the volume flow rate, cubic feet of cold air per hour and

ΔT is the difference in indoor and outdoor air temperatures.

The volume flow is the air change rate per hour. For normal residential buildings, the air change rate averages about once per hour for all rooms located above grade.

SPACE HEATING LOAD

The sum of the heat transmission losses through the building enclosure and the infiltration losses is the design hourly heat loss rate for the building. The space heating load for a building, based on heating degree-days (DD), is calculated from the design heat loss rate as follows:

$$\frac{\text{Design Heat Loss Rate}}{\text{Design Temperature Diff.}} \times 24 = \text{Space heating load, Btu/DD} \qquad [13\text{-}5]$$

The monthly and annual heating loads are then calculated using the heating degree-day values in Table 13-2 as:

$$\text{Heating Load (Btu)} = \frac{\text{Btu}}{\text{DD}} \times \text{(heating degree-days)} \qquad [13\text{-}6]$$

As an example, assume that a building has a heat requirement of 16,000 Btu/DD. The January heating degree-days is 1000, and the annual heating degree-days is 5000. The heat required in January is:

$$16{,}000\,\frac{\text{Btu}}{\text{DD}} \times 1000\ \text{DD} = 16\ \text{m Btu}$$

and the annual heat requirement is:

$$16{,}000\ \frac{\text{Btu}}{\text{DD}} \times 5000\ \text{DD} = 80\ \text{m Btu per year.}$$

DOMESTIC HOT WATER HEATING LOAD

The amount of hot water used in residential buildings is about 20 gallons per person per day and the heat required to raise the temperature of the incoming water from about 40°F in winter to 140°F can be computed from:

$$H_w\left(\frac{\text{Btu}}{\text{day}}\right) = \text{(No. of occupants)} \times 20\,\frac{\text{gallons}}{\text{(person)(day)}} \times 1\ \frac{\text{Btu}}{\text{(lb)(°F)}}$$

$$\times\ (140 - 40\text{°F}) \times 8.34\ \frac{\text{lb}}{\text{gal}}$$

or,

$$H_w = \text{(No. of occupants)} \times 16{,}680\ \frac{\text{Btu}}{\text{(person)(day)}}\ .$$

EXAMPLES

EXAMPLE 13-1

In this example, calculations are made to determine the U value of an exterior wall. The 1/k, R, and U values are given in Table 13-1.

	Thickness inches	1/k	R value	
			Uninsulated	Insulated
Outside surface air film (15 mph)			0.17	0.17
Wood bevel siding, 1/2 x 8, lapped			0.81	0.81
Ins. bd. sheathing, reg. density	.5	2.63	1.32	1.32
Air space	3.5		1.01	
Insulation	3.5		0.00	11
Gypsumboard	.5	0.90	0.45	0.45
Inside surface air film			0.68	0.68
Totals (Σ)			4.44	14.43

For the uninsulated wall, $U = 1/\Sigma R = 1/4.44 = 0.23$ Btu/(hr)(ft^2)(°F), which is lower than the approximate value of 0.28 given in Table 13-1. For the insulated wall, $U = 1/\Sigma R = 1/14.34 = 0.07$ Btu/(hr)(ft^2)(°F), which compares to the value of 0.08 given in Table 13-1. Variations can occur with the materials used in the wall.

EXAMPLE 13-2

Calculate the January heating load (L, Btu/month), and the annual heating load (H, million Btu) for the following home:

Location: Albuquerque, New Mexico
Indoor Design Temperature: 70°F
Ceiling Height: 8'-0"

House Construction:

Exterior Walls:
- 4" common brick
- 1/2" plywood
- 2 x 4 studs
- R-11 insulation
- 1/2" plasterboard

Floor construction over vented crawlspace:
- 25/32" hardwood finish flooring
- building paper
- 1" plywood sub-floor
- air space
- R-11 insulation (applied to underside of joists)

Windows: Storm windows

Exterior: 1-1/2" solid core door

Ceiling construction with vented attic space above:
- 1/2" plasterboard
- R-19 insulation

House is 51' x 27', and has one wood exterior door 3' x 6'-8", and one double glass wood frame sliding patio door with 1/4" air space, 7' x 6'-8"

The windows are as follows:

Number	Size
4	6' x 4'
3	3' x 5'
2	2' x 5'
1	2' x 3'
1	5' x 8'

The ducts are not installed within the insulation envelope.

Solution

Compute the U values for the various building sections as follows:

Exterior Wall	Thickness inches	1/k	R
Outside surface air film (15 mph)			0.17
Common brick	4	0.20	0.80
Plywood	.5	1.24	0.62
R-11 insulation			11
Plasterboard	.5	0.90	0.45
Inside surface air film			0.68
Total (Σ)			13.72

$U = 1/\Sigma R = 1/13.72 = 0.07$ Btu/(hr)(ft^2)(°F)

Floor	Thickness inches	1/k	R
Inside surface air film			0.92
Hardwood finish flooring	25/32		0.68
Building paper			0.06
Plywood sub-floor	1	1.24	1.24
Air space			1.01
R-11 insulation			11
Outside surface air film			0.17
Total (Σ)			15.08

$$U = 1/\Sigma R = 1/15.08 = 0.07 \text{ Btu/(hr)(ft}^2\text{)(°F)}$$

Ceiling	Thickness inches	1/k	R
Inside surface air film			0.61
Plasterboard	.5	0.9	0.45
R-19 insulation			19
Outer surface air film			0.17
Total (Σ)			20.23

$$U = 1/\Sigma R = 1/20.23 = 0.05 \text{ Btu/(hr)(ft}^2\text{)(°F)}$$

The winter design outdoor temperature for Albuquerque, New Mexico, is given in Table 13-2 as 14°F. With the room temperature set at 70°F, $\Delta T = T_R - T_o = 70 - 14 = 56°F$. The values of U for this house are summarized below:

	U, Btu/(hr)(ft^2)(°F)
Exterior wall	0.07
Windows	0.56
Floor	0.07
Ceiling	0.05
Exterior door (1-1/2" solid core)	0.49
Double glass sliding patio door	0.65

The heat loss calculations and the domestic hot water load can be systematized by using worksheets TA-1. The heating loads for the house of example 1 are worked out on the worksheets shown on the following pages. Additional worksheet blanks are included at the end of this module for the convenience of the user. It is suggested that extra copies be made for office use from the blank copies that are provided.

Worksheet TA-1
Sheet 1 of 2

Building Heat Load Calculations

Job Example 13-2
Number of Occupants 4
Computed by
Date Jan 13, 1977
Location Albuquerque N.M.
Latitude 35°N

Indoor temperature, T_R, 70 °F
Design winter outdoor temperature, T_O, 14 °F
Design temperature difference 56 °F
Design degree-day, 65 - T_O, 51 °F

Building Dimensions:
Above Grade: Length 51 ft Width 27 ft Ceiling Height 8 ft
Below Grade: Length 0 ft Width 0 ft Depth 0 ft
Concrete Floor Slab: Exposed perimeter 0 ft

Exterior Wall Area: $8 \times (51 + 27) \times 2 = 1248$ ft^2

Window Area: $4 \times (6 \times 4) + 3 \times (3 \times 5) + 2 \times (2 \times 5)$
$+ 1 \times (2 \times 3) + 1 \times (5 \times 8) = 207$ ft^2

Door Area: Wood Door $3 \times 6'\text{-}8'' = 20$ ft^2
Patio Door $7 \times 6'\text{-}8'' = 47$ ft^2

Net Exterior Wall Area: $1248 - 207 - 20 - 47 = 974$ ft^2

Ceiling Area: $27 \times 51 = 1377$ ft^2

Floor Area: $27 \times 51 = 1377$ ft^2

Basement Wall Area: 0

Heating Degree-Days:* January 930 °F-days
Annual 4348 °F-days

* From Table 13-2

Worksheet TA-1
Sheet 2 of 2

		U $\frac{Btu}{(hr)(ft^2)(^{o}F)}$	A	ΔT °F ($T_R - T_o$)	h = UA ΔT Btu/hr
Exterior Walls (net)		0.07	974	56	3820
Basement Walls	Above grade				—
	Below grade			*	—
Windows and Sliding Patio Doors	Single				—
	Double	0.65	47	56	1710
	Triple				—
	Storm	0.56	207	56	6490
Exterior Slab Doors		0.49	20	56	550
Floors	Over Crawlspace	0.07	1377	56	5400
	Concrete Slab on Grade				—
	Basement				—
Ceiling		0.05	1377	56	3860
Subtotal (walls, windows, doors, floors, ceiling)					21,830
Infiltration: (0.018) x 27x51x8 ft^3 x 56 °F					11,100
Duct = 10% of subtotal (if ducts not in insulation envelope)					2180
Design Heating Load: Btu/hr					35,110
Design Heating Load: Btu/DD Design Heating Load (Btu/hr) X (24 hr/Design TD)					15,050
January Heating Load: m Btu (Btu/DD) X (January DD)					14.0
Annual Heating Load: m Btu (Btu/DD) X (Annual DD)					65.4

$^{*}\Delta T = T_R - 45^{o}$

DOMESTIC HOT WATER LOAD

Number of occupants X 16,680 Btu/day	66,720
January Load (m Btu) (Btu/day) x 31 x 10^{-6}	2.1
Annual Load (m Btu) (January load x 12)	24.8

PROBLEMS

PROBLEM 13-1

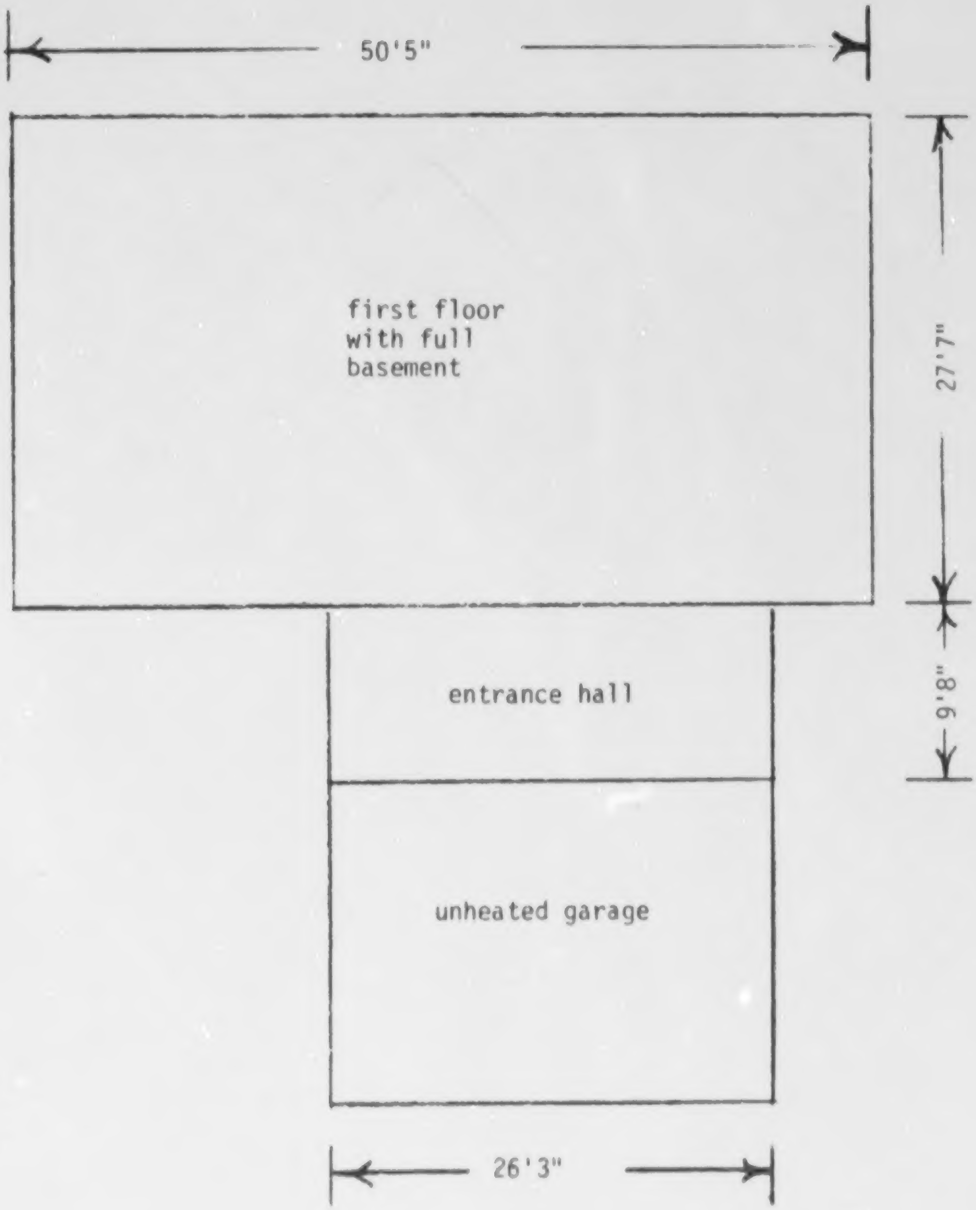
For the home plan shown in Figure 13-1, calculate the January and annual heating loads. Assume that an internal temperature of 68°F is to be maintained. The home is located in Fort Collins, Colorado, where the design winter outdoor air temperature is -9°F. The three-bedroom home will be occupied by four people. The first floor ceiling height is 97 inches, the entrance hall ceiling height is 111 inches, and the basement ceiling height is 92 inches. The entire basement is below grade and is heated. The entrance hall has a concrete slab floor with no perimeter insulation. All ducts are within the building envelope. Basement walls are 7.5-inch thick concrete.

All exterior doors are in the hall. Their sizes are given in the following table:

Door	Thickness	Size
Front door	1.5"	81" x 65"
2 doors between entrance hall and garage (each)	1.5"	80" x 29"
2 sliding patio doors (metal frame) one single glass and one double glass (.25" air space) each		80" x 35.5"

The house contains the following windows, which are all storm windows except as specified:

Window	Size
Entrance hall (single glass)	16" x 57"
Kitchen window	32" x 35"
2 dining room windows, each	32" x 43"
2 living room (.25" air space) double glazed (not storm windows), each	13" x 61"
2 living room picture windows, each	47" x 53"
4 bedroom windows, each	32" x 43"
6 basement windows, each	21" x 32"


50'5"
first floor
with full
basement
27'7"
9'8"
entrance hall
unheated garage
26'3"

Scale: 1" = 10'

Figure 13-1. Outline of the Building in Problem 1.

The ceiling consists of 1/2-inch plasterboard and insulating batts 5-1/4" thick. The exterior wall consists of 1/2" plasterboard, 3-1/2" batt insulation, and 1/4" hardboard siding. The January heating degree-days for Fort Collins is 1,250 (°F)(days) and the annual degree-days is 6,300 (°F)(days). This home is heated with natural gas.

Answers:

The January heating load is 20.8 m Btu and the annual heating load is 104.6 m Btu.

WORKSHEET TA-1

Extra worksheets TA-1 are provided with this module for solving problem 13-1 of the preceding section. The forms may also be used in general practice.

REFERENCES

1. Load Calculation Guide (1 and 2 Family Dwellings) for Heating and Air Conditioning, Better Heating and Cooling Bureau, Sheet Metal and Air Conditioning Contractor's National Association, Inc. (SMACNA), 8224 Old Courthouse Road, Tyson's Corner, Vienna, Virginia, 1975.
2. Loan Calculation for Residential Winter and Summer Air Conditioning manual J, National Environmental Systems Contractors Association (NESCA), 1501 Wilson Boulevard, Arlington, Virginia, Fourth Edition, Second Printing, 1975.
3. Insulation Manual, NAHB (National Association of Home Builders) Research Foundation, Inc., P.O. Box 1627, Rockville, Maryland, September 1971.

Worksheet TA-1
Sheet 1 of 2

Building Heat Load Calculations

Job Solution for Prob. 13-1
Number of Occupants 4
Computed by
Date Jan 13, 1977
Location Fort Collins, Colo.
Latitude 40+° N

Indoor temperature, T_R, 68 °F
Design winter outdoor temperature, T_O, -9 °F
Design temperature difference 77 °F
Design degree-day, $65 - T_O$, 72 °F

Building Dimensions:
Above Grade: Length 50.4 ft Width 27.6 ft Ceiling Height 8 ft (9.25) Hall
Below Grade: Length ft Width ft Depth 7.67 ft
Concrete Floor Slab: Exposed perimeter ft

Exterior Wall Area: $8 \times (50.4 + 27.6) \times 2 - (26.25 \times 8) +$
$(9.25 \times 9.67 \times 2) +$ Garage-Hall $(9.25 \times 26.25) =$ 1460 ft^2

Window Area: $(1 \times 2.67 \times 2.92) + (2 \times 2.67 \times 3.58) +$
$(2 \times 3.92 \times 4.42) + (4 \times 2.67 \times 3.53) + 6(1.75 \times 2.67)$ Basement.

Door Area: (6.75×5.48)
Garage $(2 \times 6.67 \times 2.42)$ Patio $(6.67 \times 2.96) \times 2$

Net Exterior Wall Area: $1038 + 179 + 243 - 100 - 37 - 32 - 37 - 40$
1214 ft^2

Ceiling Area: $(50.4 \times 27.6) + (9.67 \times 26.25)$ 1645 ft^2

Floor Area: On Slab 46 ft exposed edge
Basement 50.4×27.6 1391 ft^2

Basement Wall Area: $7.67 \times (50.4 + 27.6) \times 2 - 28$ 1169 ft^2

Heating Degree-Days:* January 1250 °F-days
Annual 6300 °F-days

* From Table 13-2

Worksheet TA-1
Sheet 2 of 2

		U Btu (hr)(ft²)(°F)	A	ΔT °F (T_R - T_o)	h = UA ΔT Btu/hr
Exterior Walls (net)		.08	1214	77	7478
Basement Walls	Above grade				
	Below grade	.06	1169	23 *	1613
Windows and Sliding Patio Doors	Single	1.13	26	77	2262
	Double	0.65	31	77	1551
	Triple				
	Storm	0.56	128	77	5519
Exterior Slab Doors		0.49	69	77	2603
Floors	Over Crawlspace				
	Concrete Slab on Grade	0.81	46	44	1639
	Basement	.06	1440	23	1987
Ceiling		.05	1645	77	6333
Subtotal (walls, windows, doors, floors, ceiling)					
Infiltration: (0.018) x 50.4 x 27.8 x 8 + 9.25 x 26.25 x 9.67 ft³ x 77 °F					18.790
Duct = 10% of subtotal (if ducts not in insulation envelope)					—
Design Heating Load: Btu/hr					49,775
Design Heating Load: Btu/DD Design Heating Load (Btu/hr) X (24 hr/Design TD)					15,514
January Heating Load: m Btu (Btu/DD) X (January DD)					19.4
Annual Heating Load: m Btu (Btu/DD) X (Annual DD)					97.7

* ΔT = T_R - 45°

DOMESTIC HOT WATER LOAD

Number of occupants X 16,680 Btu/day	66,720
January Load (m Btu) (Btu/day) x 31 x 10^{-6}	2.1
Annual Load (m Btu) (January load x 12)	24.8

Table 13-2. Data Values for Heating Load Computations*

	NORMAL TOTAL HEATING DEGREE DAYS (Base 65°)													Design T_o °F	
STATE AND STATION	JULY	AUG	SEPT	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUNE	ANNUAL	WIN.†	SUMM.‖
ALA: Birmingham	0	0	6	93	363	555	592	462	363	108	9	0	2551	19	97
Huntsville	0	0	12	127	426	663	694	557	434	138	19	0	3070	13	97
Mobile	0	0	0	22	213	357	415	300	211	42	0	0	1560	26	95
Montgomery	0	0	0	68	330	527	543	417	316	90	0	0	2291	22	98
ALASKA: Anchorage	245	291	516	930	1284	1572	1631	1316	1293	879	592	315	10864	-25	73
Annette	242	208	327	567	738	899	949	837	843	648	490	321	7069		
Barrow	803	840	1035	1500	1971	2362	2517	2332	2468	1944	1445	957	20174	-45	58
Barter Is.	735	775	987	1482	1944	2337	2536	2369	2477	1923	1373	924	19862		
Bethel	319	394	612	1042	1434	1866	1903	1590	1655	1173	806	402	13196		
Cold Bay	474	425	525	772	918	1122	1153	1036	1122	951	791	591	9880		
Cordova	366	391	522	781	1017	1221	1299	1086	1113	864	660	444	9764		
Fairbanks	171	332	642	1203	1833	2254	2359	1901	1739	1068	555	222	14279	-53	82
Juneau	301	338	483	725	921	1135	1237	1070	1073	810	601	381	9075	- 7	75
King Salmon	313	322	513	908	1290	1606	1600	1333	1411	966	673	408	11343		
Kotzebue	381	446	723	1249	1728	2127	2192	1932	2080	1554	1057	636	16105		
McGrath	208	338	633	1184	1791	2232	2294	1817	1758	1122	648	258	14283		
Nome	481	496	693	1094	1455	1820	1879	1666	1770	1314	930	573	14171	-32	66
Saint Paul	605	539	612	862	963	1197	1228	1168	1265	1098	936	726	11199		
Shemya	577	475	501	784	876	1042	1045	958	1011	885	837	696	9687		
Yakutat	338	347	474	716	936	1144	1169	1019	1042	840	632	435	9092		
ARIZ: Flagstaff	46	68	201	558	867	1073	1169	991	911	651	437	180	7152	0	84
Phoenix	0	0	0	22	234	415	474	328	217	75	0	0	1765	31	108
Prescott	0	0	27	245	579	797	865	711	605	360	158	15	4362	15	96
Tucson	0	0	0	25	231	406	471	344	242	75	6	0	1800	29	105
Winslow	0	0	6	245	711	1008	1054	770	601	291	96	0	4782	9	97
Yuma	0	0	0	0	148	319	363	228	130	29	0	0	1217	37	111
ARK: Fort Smith	0	0	12	127	450	704	781	596	456	144	22	0	3292	15	101
Little Rock	0	0	9	127	465	716	756	577	434	126	9	0	3219	19	99
Texarkana	0	0	0	78	345	561	626	468	350	105	0	0	2533	22	99
CALIF: Bakersfield	0	0	0	37	282	502	546	364	267	105	19	0	2122	31	103
Bishop	0	0	42	248	576	797	874	666	539	306	143	36	4227		
Blue Canyon	34	50	120	347	579	766	865	781	791	582	397	195	5507		
Burbank	0	0	6	43	177	301	366	277	239	138	81	18	1646	36	97

*From Climatic Atlas of the United States, U.S. Department of Commerce, Env. Sci. Serv. Adm. June 1968

†From Table 1, Chapter 33, ASHRAE Handbook of Fundamentals 1972 (99% of time warmer than this temperature)

‖From Table 1, Chapter 33, ASHRAE Handbook of Fundamentals 1972 (1% of time dry bulb temperature is greater)

NORMAL TOTAL HEATING DEGREE DAYS (Base 65°)														Design T_o °F	
STATE AND STATION	JULY	AUG	SEPT	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUNE	ANNUAL	WIN.	SUMM.
CALIF: Eureka	270	257	258	329	414	499	546	470	505	438	372	285	4643	32	67
Fresno	0	0	0	78	339	558	586	406	319	150	56	0	2492	28	101
Long Beach	0	0	12	40	156	288	375	297	267	168	90	18	1711	36	87
Los Angeles	28	22	42	78	180	291	372	302	288	219	158	81	2061	42	94
Mt. Shasta	25	34	123	406	696	902	983	784	738	525	347	159	5722		
Oakland	53	50	45	127	309	481	527	400	353	255	180	90	2870	35	85
Point Arguello	202	186	162	205	291	400	474	392	403	339	298	243	3595		
Red Bluff	0	0	0	53	318	555	605	428	341	168	47	0	2515		
Sacramento	0	0	12	81	363	577	614	442	360	216	102	6	2773	30	100
Sandberg	0	0	30	202	480	691	778	661	620	426	264	57	4209		
San Diego	6	0	15	37	123	251	313	249	202	123	84	36	1439	42	86
San Francisco	81	78	60	143	306	462	508	395	363	279	214	126	3015	42	80
Santa Catalina	16	0	9	50	165	279	353	308	326	249	192	105	2052		
Santa Maria	99	93	96	146	270	391	459	370	363	282	233	165	2967	32	85
COLO: Alamosa	65	99	279	639	1065	1420	1476	1162	1020	696	440	168	8529	-17	84
Colorado Springs	9	25	132	456	825	1032	1128	938	893	582	319	84	6423	- 1	90
Denver	6	9	117	428	819	1035	1132	938	887	558	288	66	6283	- 2	92
Grand Junction	0	0	30	313	786	1113	1209	907	729	387	146	21	5641	8	96
Pueblo	0	0	54	326	750	986	1085	871	772	429	174	15	5462	- 5	96
CONN: Bridgeport	0	0	66	307	615	986	1079	966	853	510	208	27	5617	4	90
Hartford	0	6	99	372	711	1119	1209	1061	899	495	177	24	6172	1	90
New Haven	0	12	87	347	648	1011	1097	991	871	543	245	45	5897	5	88
DEL: Wilmington	0	0	51	270	588	927	980	874	735	387	112	6	4930	12	93
FLA: Apalachicola	0	0	0	16	153	319	347	260	180	33	0	0	1308		
Daytona Beach	0	0	0	0	75	211	248	190	140	15	0	0	879	32	94
Fort Myers	0	0	0	0	24	109	146	101	62	0	0	0	442	38	94
Jacksonville	0	0	0	12	144	310	332	246	174	21	0	0	1239	29	96
Key West	0	0	0	0	0	28	40	31	9	0	0	0	108	55	90
Lakeland	0	0	0	0	57	164	195	146	99	0	0	0	661	35	95
Miami Beach	0	0	0	0	0	40	56	36	9	0	0	0	141	45	91
Orlando	0	0	0	0	72	198	220	165	105	6	0	0	766	33	96
Pensacola	0	0	0	19	195	353	400	277	183	36	0	0	1463	29	92
Tallahassee	0	0	0	28	198	360	375	286	202	36	0	0	1485	25	96

	NORMAL TOTAL HEATING DEGREE DAYS (Base 65°)													Design T_o °F	
STATE AND STATION	JULY	AUG	SEPT	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUNE	ANNUAL	WIN.	SUMM.
FLA: Tampa	0	0	0	0	60	171	202	148	102	0	0	0	683	36	92
West Palm Beach	0	0	0	0	6	65	87	64	31	0	0	0	253	40	92
GA: Athens	0	0	12	115	405	632	642	529	431	141	22	0	2929	17	96
Atlanta	0	0	18	127	414	626	639	529	437	168	25	0	2983	18	95
Augusta	0	0	0	78	333	552	549	445	350	90	0	0	2397	20	98
Columbus	0	0	0	87	333	543	552	434	338	96	0	0	2383	23	98
Macon	0	0	0	71	297	502	505	403	295	63	0	0	2136	23	98
Rome	0	0	24	161	474	701	710	577	468	177	34	0	3326	16	97
Savannah	0	0	0	47	246	437	437	353	254	45	0	0	1819	24	96
Thomasville	0	0	0	25	198	366	394	305	208	33	0	0	1529		
IDAHO: Boise	0	0	132	415	792	1017	1113	854	722	438	245	81	5809	4	96
Idaho Falls 46W	16	34	270	623	1056	1370	1538	1249	1085	651	391	192	8475		
Idaho Falls 42NW	16	40	282	648	1107	1432	1600	1291	1107	657	388	192	8760		
Lewiston	0	0	123	403	756	933	1063	815	694	426	239	90	5542	6	98
Pocatello	0	0	172	493	900	1166	1324	1058	905	555	319	141	7033	- 8	94
ILL: Cairo	0	0	36	164	513	791	856	680	539	195	47	0	3821		
Chicago	0	0	81	326	753	1113	1209	1044	890	480	211	48	6155	- 3	94
Moline	0	9	99	335	774	1181	1314	1100	918	450	189	39	6408	- 7	94
Peoria	0	6	87	326	759	1113	1218	1025	849	426	183	33	6025	- 2	94
Rockford	6	9	114	400	837	1221	1333	1137	961	516	236	60	6830	- 7	92
Springfield	0	0	72	291	696	1023	1135	935	769	354	136	18	5429	- 1	95
IND: Evansville	0	0	66	220	606	896	955	767	620	237	68	0	4435	6	96
Fort Wayne	0	9	105	378	783	1135	1178	1028	890	471	189	39	6205	0	93
Indianapolis	0	0	90	316	723	1051	1113	949	809	432	177	39	5699	0	93
South Bend	0	6	111	372	777	1125	1221	1070	933	525	239	60	6439	- 2	92
IOWA: Burlington	0	0	93	322	768	1135	1259	1042	859	426	177	33	6114	- 4	95
Des Moines	0	9	99	363	837	1231	1398	1163	967	489	211	39	6808	- 7	95
Dubuque	12	31	156	450	906	1287	1420	1204	1026	546	260	78	7376	-11	92
Sioux City	0	9	108	369	867	1240	1435	1198	989	483	214	39	6951	-10	96
Waterloo	12	19	138	428	909	1296	1460	1221	1023	531	229	54	7320	-12	91

NORMAL TOTAL HEATING DEGREE DAYS (Base 65^{o})														Design T_{o} ^{o}F	
STATE AND STATION	JULY	AUG	SEPT	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUNE	ANNUAL	WIN.	SUMM.
KANSAS: Concordia	0	0	57	276	705	1023	1163	935	781	372	149	18	5479		
Dodge City	0	0	33	251	666	939	1051	840	719	354	124	9	4986	3	99
Goodland	0	6	81	381	810	1073	1166	955	884	507	236	42	6141	- 2	99
Topeka	0	0	57	270	672	980	1122	893	722	330	124	12	5182	3	99
Wichita	0	0	33	229	618	905	1023	804	645	270	87	6	4620	5	102
KY: Covington	0	0	75	291	669	983	1035	893	756	390	149	24	5265	3	93
Lexington	0	0	54	239	609	902	946	818	685	325	105	0	4683	6	94
Louisville	0	0	54	248	609	890	930	818	682	315	105	9	4660	8	96
LA: Alexandria	0	0	0	56	273	431	471	361	260	69	0	0	1921	25	97
Baton Rouge	0	0	0	31	216	369	409	294	208	33	0	0	1560	25	96
Burrwood	0	0	0	0	96	214	298	218	171	27	0	0	1024		
Lake Charles	0	0	0	19	210	341	381	274	195	39	0	0	1459	29	95
New Orleans	0	0	0	19	192	322	363	258	192	39	0	0	1385	32	93
Shreveport	0	0	0	47	297	477	552	426	304	81	0	0	2184	22	99
MAINE: Caribou	78	115	336	682	1044	1535	1690	1470	1308	858	468	183	9767	-18	85
Portland	12	53	195	508	807	1215	1339	1182	1042	675	372	111	7511	- 5	88
MD: Baltimore	0	0	48	264	585	905	936	820	679	327	90	0	4654	16	94
Frederick	0	0	66	307	624	955	995	876	741	384	127	12	5087	7	94
MASS: Blue Hill Obsy	0	22	108	381	690	1085	1178	1053	936	579	267	69	6368		
Boston	0	9	60	316	603	983	1088	972	846	513	208	36	5634	6	91
Nantucket	12	22	93	332	573	896	992	941	896	621	384	129	5891		
Pittsfield	25	59	219	524	831	1231	1339	1196	1063	660	326	105	7578	- 1	86
Worcester	6	34	147	450	774	1172	1271	1123	998	612	304	78	6969	1	89
MICH: Alpena	63	105	273	580	912	1268	1404	1299	1218	777	446	156	8506	- 5	87
Detroit (City)	0	0	87	360	738	1088	1181	1058	936	522	220	42	6232	4	92
Escanaba	59	87	243	539	924	1293	1445	1296	1203	777	456	159	8481	- 7	82
Flint	16	40	159	465	843	1212	1330	1198	1066	639	319	90	7377	- 1	89
Grand Rapids	9	28	135	434	804	1147	1259	1134	1011	549	279	75	6894	2	91
Lansing	6	22	138	431	813	1163	1262	1142	1011	579	273	69	6909	2	89
Marquette	59	81	240	527	936	1268	1411	1268	1187	771	468	177	8393	- 8	88
Muskegon	12	28	120	400	762	1088	1209	1100	995	594	310	78	6696	4	87
Sault Ste. Marie	96	105	279	580	951	1367	1525	1380	1277	810	477	201	9048	-12	83

NORMAL TOTAL HEATING DEGREE DAYS (Base 65^{o})														Design T_o °F	
STATE AND STATION	JULY	AUG	SEPT	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUNE	ANNUAL	WIN.	SUMM.
MINN: Duluth	71	109	330	632	1131	1581	1745	1518	1355	840	490	198	10000	-19	85
Internat'l Falls	71	112	363	701	1236	1724	1919	1621	1414	828	443	174	10606	-29	86
Minneapolis	22	31	189	505	1014	1454	1631	1380	1166	621	288	81	8382	-14	92
Rochester	25	34	186	474	1005	1438	1593	1366	1150	630	301	93	8295	-17	90
Saint Cloud	28	47	225	549	1065	1500	1702	1445	1221	666	326	105	8879	-20	90
MISS: Jackson	0	0	0	65	315	502	546	414	310	87	0	0	2239	21	98
Meridian	0	0	0	81	339	518	543	417	310	81	0	0	2289	20	97
Vicksburg	0	0	0	53	279	462	512	384	282	69	0	0	2041	23	97
MO: Columbia	0	0	54	251	651	967	1076	874	716	324	121	12	5046	2	97
Kansas	0	0	39	220	612	905	1032	818	682	294	109	0	4711	4	100
St. Joseph	0	6	60	285	708	1039	1172	949	769	348	133	15	5484	- 1	97
St. Louis	0	0	60	251	627	936	1026	848	704	312	121	15	4900	7	96
Springfield	0	0	45	223	600	877	973	781	660	291	105	6	4561	5	97
MONT: Billings	6	15	186	487	897	1135	1296	1100	970	570	285	102	7049	-10	94
Glasgow	31	47	270	608	1104	1466	1711	1439	1187	648	335	150	8996	-25	96
Great Falls	28	53	258	543	921	1169	1349	1154	1063	642	384	186	7750	-20	91
Havre	28	53	306	595	1065	1367	1584	1364	1181	657	338	162	8700	-22	91
Helena	31	59	294	601	1002	1265	1438	1170	1042	651	381	195	8129	-17	90
Kalispell	50	99	321	654	1020	1240	1401	1134	1029	639	397	207	8191	- 7	88
Miles City	6	6	174	502	972	1296	1504	1252	1057	579	276	99	7723	-19	97
Missoula	34	74	303	651	1035	1287	1420	1120	970	621	391	219	8125	- 7	92
NEBR: Grand Island	0	6	108	381	834	1172	1314	1089	908	462	211	45	6530	- 6	98
Lincoln	0	6	75	301	726	1066	1237	1016	834	402	171	30	5864	- 4	100
Norfolk	9	0	111	397	873	1234	1414	1179	983	498	233	48	6979	-11	97
North Platte	0	6	123	440	885	1166	1271	1039	930	519	248	57	6684	- 6	97
Omaha	0	12	105	357	828	1175	1355	1126	939	465	208	42	6612	- 5	97
Scottsbluff	0	0	138	459	876	1128	1231	1008	921	552	285	75	6673	- 8	96
Valentine	9	12	165	493	942	1237	1395	1176	1045	579	288	84	7425		
NEV: Elko	9	34	225	561	924	1197	1314	1036	911	621	409	192	7433	-13	94
Ely	28	43	234	592	939	1184	1308	1075	977	672	456	225	7733	- 6	90
Las Vegas	0	0	0	78	387	617	688	487	335	111	6	0	2709	23	108
Reno	43	87	204	490	801	1026	1073	823	729	510	357	189	6332	12	94
Winnemucca	0	34	210	536	876	1091	1172	916	837	573	363	153	6761	1	97

NORMAL TOTAL HEATING DEGREE DAYS (Base 65^{o})														Design T_o °F	
STATE AND STATION	JULY	AUG	SEPT	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUNE	ANNUAL	WIN.	SUMM.
NH: Concord	6	50	177	505	822	1240	1358	1184	1032	636	298	75	7383	-11	91
Mt. Wash. Obsy.	493	536	720	1057	1341	1742	1820	1663	1652	1260	930	603	13817		
NJ: Atlantic City	0	0	39	251	549	880	936	848	741	420	133	15	4812	14	91
Newark	0	0	30	248	573	921	983	876	729	381	118	0	4859	11	94
Trenton	0	0	57	264	576	924	989	885	753	399	121	12	4980	12	92
NM: Albuquerque	0	0	12	229	642	868	930	703	595	288	81	0	4348	14	96
Clayton	0	6	66	310	699	899	986	812	747	429	183	21	5158		
Raton	9	28	126	431	825	1048	1116	904	834	543	301	63	6228	- 2	92
Roswell	0	0	18	202	573	806	840	641	481	201	31	0	3793	16	101
Silver City	0	0	6	183	525	729	791	605	581	261	87	0	3705	14	95
NY: Albany	0	19	138	440	777	1194	1311	1156	992	564	239	45	6875	1	91
Binghamton (AP)	22	65	201	471	810	1184	1277	1154	1045	645	313	99	7286	- 2	91
Binghamton (PO)	0	28	141	406	732	1107	1190	1081	949	543	229	45	6451		
Buffalo	19	37	141	440	777	1156	1256	1145	1039	645	329	78	7062	- 5	90
Central Park	0	0	30	233	540	902	986	885	760	408	118	9	4871	11	94
JF Kennedy Intl.	0	0	36	248	564	933	1029	935	815	480	167	12	5219	17	91
LaGuardia	0	0	27	223	528	887	973	879	750	414	124	6	4811	12	93
Rochester	9	31	126	415	747	1125	1234	1123	1014	597	279	48	6748	2	91
Schenectady	0	22	123	422	756	1159	1283	1131	970	543	211	30	6650	- 5	90
Syracuse	6	28	132	415	744	1153	1271	1140	1004	570	248	45	6756	- 2	90
NC: Asheville	0	0	48	245	555	775	784	683	592	273	87	0	4042	13	91
Cape Hatteras	0	0	0	78	273	521	580	518	440	177	25	0	2612		
Charlotte	0	0	6	124	438	691	691	582	481	156	22	0	3191	18	96
Greensboro	0	0	33	192	513	778	784	672	552	234	47	0	3805	14	94
Raleigh	0	0	21	164	450	716	725	616	487	180	34	0	3393	16	95
Wilmington	0	0	0	74	291	521	546	462	357	96	0	0	2347	23	94
Winston Salem	0	0	21	171	483	747	753	652	524	207	37	0	3595	14	94
N. DAK: Bismarck	34	28	222	577	1083	1463	1708	1442	1203	645	329	117	8851	-24	95
Devils Lake	40	53	273	642	1191	1634	1872	1579	1345	753	381	138	9901	-23	93
Fargo	28	37	219	574	1107	1569	1789	1520	1262	690	332	99	9226	-22	92
Williston	31	43	261	601	1122	1513	1758	1473	1262	681	357	141	9243	-21	94

NORMAL TOTAL HEATING DEGREE DAYS (Base 65°)													Design T_o °F	
STATE AND STATION	JULY	AUG	SEPT	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUNE	ANNUAL	WIN.	SUMM.
OHIO: Akron	0	9	96	381	726	1070	1138	1016	871	489	202	39	6037	1	89
Cincinnati	0	0	54	248	612	921	970	837	701	336	118	9	4806	8	94
Cleveland	9	25	105	384	738	1088	1159	1047	918	552	260	66	6351	2	91
Columbus	0	6	84	347	714	1039	1088	949	809	426	171	27	5660	2	92
Dayton	0	6	78	310	696	1045	1097	955	809	429	167	30	5622	0	92
Mansfield	9	22	114	397	768	1110	1169	1042	924	543	245	60	6403	1	91
Sandusky	0	6	66	313	684	1032	1107	991	868	495	198	36	5796	4	92
Toledo	0	16	117	406	792	1138	1200	1056	924	543	242	60	6494	1	92
Youngstown	6	19	120	412	771	1104	1169	1047	921	540	248	60	6417	1	89
OKLA: Oklahoma City	0	0	15	164	498	766	868	664	527	189	34	0	3725	11	100
Tulsa	0	0	18	158	522	787	893	683	539	213	47	0	3860	12	102
OREG: Astoria	146	130	210	375	561	679	753	622	636	480	363	231	5186	27	79
Burns	12	37	210	515	867	1113	1246	988	856	570	366	177	6957		
Eugene	34	34	129	366	585	719	803	627	589	426	279	135	4726	22	91
Meacham	84	124	288	580	918	1091	1209	1005	983	726	527	339	7874		
Medford	0	0	78	372	678	871	918	697	642	432	242	78	5008	21	98
Pendleton	0	0	111	350	711	884	1017	773	617	396	205	63	5127	3	97
Portland	25	28	114	335	597	735	825	644	586	396	245	105	4635	26	91
Roseburg	22	16	105	329	567	713	766	608	570	405	267	123	4491	25	93
Salem	37	31	111	338	594	729	822	647	611	417	273	144	4754	21	92
Sexton Summit	81	81	171	443	666	874	958	809	818	609	465	279	6524		
PA: Allentown	0	0	90	353	693	1045	1116	1002	849	471	167	24	5810	3	92
Erie	0	25	102	391	714	1063	1169	1081	973	585	288	60	6451	7	88
Harrisburg	0	0	63	298	648	992	1045	907	766	396	124	12	5251	9	92
Philadelphia	0	0	60	291	621	964	1014	890	744	390	115	12	5101	11	93
Pittsburgh	0	9	105	375	726	1063	1119	1002	874	480	195	39	5987	7	90
Reading	0	0	54	257	597	939	1001	885	735	372	105	0	4945	6	92
Scranton	0	19	132	434	762	1104	1156	1028	893	498	195	33	6254	2	89
Williamsport	0	9	111	375	717	1073	1122	1002	856	468	177	24	5934	1	91
RI: Block Island	0	16	78	307	594	902	1020	955	877	612	344	99	5804		
Providence	0	16	96	372	660	1023	1110	988	868	534	236	51	5954	6	89

	NORMAL TOTAL HEATING DEGREE DAYS (Base 65°)													Design T_o °F	
STATE AND STATION	JULY	AUG	SEPT	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUNE	ANNUAL	WIN.	SUMM.
SC: Charleston	0	0	0	59	282	471	487	389	291	54	0	0	2033	26	95
Columbia	0	0	0	84	345	577	570	470	357	81	0	0	2484	20	98
Florence	0	0	0	78	315	552	552	459	347	84	0	0	2387	21	96
Greenville	0	0	0	112	387	636	648	535	434	120	12	0	2884	19	95
Spartanburg	0	0	15	130	417	667	663	560	453	144	25	0	3074	18	95
S. DAK: Huron	9	12	165	508	1014	1432	1628	1355	1125	600	288	87	8223	-16	97
Rapid City	22	12	165	481	897	1172	1333	1145	1051	615	326	126	7345	- 9	96
Sioux Falls	19	25	168	462	972	1361	1544	1285	1082	573	270	78	7839	-14	95
TENN: Bristol	0	0	51	236	573	828	828	700	598	261	68	0	4143	11	92
Chattanooga	0	0	18	143	468	698	722	577	453	150	25	0	3254	15	97
Knoxville	0	0	30	171	489	725	732	613	493	198	43	0	3494	13	95
Memphis	0	0	18	130	447	698	729	585	456	147	22	0	3232	17	98
Nashville	0	0	30	158	495	732	778	644	512	189	40	0	3578	12	97
Oak Ridge (CO)	0	0	39	192	531	772	778	669	552	228	56	0	3817		
TEXAS: Abilene	0	0	0	99	366	586	642	470	347	114	0	0	2624	17	101
Amarillo	0	0	18	205	570	797	877	664	546	252	56	0	3985	8	98
Austin	0	0	0	31	225	388	468	325	223	51	0	0	1711	25	101
Brownsville	0	0	0	0	66	149	205	106	74	0	0	0	600	36	94
Corpus Christi	0	0	0	0	120	220	291	174	109	0	0	0	914	32	95
Dallas	0	0	0	62	321	524	601	440	319	90	6	0	2363	19	101
El Paso	0	0	0	84	414	648	685	445	319	105	0	0	2700	21	100
Fort Worth	0	0	0	65	324	536	614	448	319	99	0	0	2405	20	102
Galveston	0	0	0	0	138	270	350	258	189	30	0	0	1235	32	91
Houston	0	0	0	6	183	307	384	288	192	36	0	0	1396	29	96
Laredo	0	0	0	0	105	217	267	134	74	0	0	0	797	32	103
Lubbock	0	0	18	174	513	744	800	613	484	201	31	0	3578	11	99
Midland	0	0	0	87	381	592	651	468	322	90	0	0	2591	19	100
Port Arthur	0	0	0	22	207	329	384	274	192	39	0	0	1447	29	94
San Angelo	0	0	0	68	318	536	567	412	288	66	0	0	2255	20	101
San Antonio	0	0	0	31	207	363	428	286	195	39	0	0	1549	25	99
Victoria	0	0	0	6	150	270	344	230	152	21	0	0	1173	28	98
Waco	0	0	0	43	270	456	536	389	270	66	0	0	2030	21	101
Wichita Falls	0	0	0	99	381	632	698	518	378	120	6	0	2832	15	103

NORMAL TOTAL HEATING DEGREE DAYS (Base 65^{o})														Design T_o ^oF	
STATE AND STATION	JULY	AUG	SEPT	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUNE	ANNUAL	WIN.	SUMM.
UTAH: Milford	0	0	99	443	867	1141	1252	988	822	519	279	87	6497		
Salt Lake City	0	0	81	419	849	1082	1172	910	763	459	233	84	6052	5	97
Wendover	0	0	48	372	822	1091	1178	902	729	408	177	51	4778		
VT: Burlington	28	65	207	539	891	1349	1513	1333	1187	714	353	90	8269	-12	88
VA: Cape Henry	0	0	0	112	360	645	694	633	536	246	53	0	3279		
Lynchburg	0	0	51	223	540	822	849	731	605	267	78	0	4166	15	94
Norfolk	0	0	0	136	408	698	738	655	533	216	37	0	3421	20	94
Richmond	0	0	36	214	495	784	815	703	546	219	53	0	3865	14	96
Roanoke	0	0	51	229	549	825	834	722	614	261	65	0	4150	15	94
Wash. Nat'l AP	0	0	33	217	519	834	871	762	626	288	74	0	4224		
WASH: Olympia	68	71	198	422	636	753	834	675	645	450	307	177	5236	21	85
Seattle	50	47	129	329	543	657	738	599	577	396	242	177	4424	23	82
Seattle Boeing	34	40	147	384	624	763	831	655	608	411	242	99	4838		
Seattle Tacoma	56	62	162	391	633	750	828	678	657	474	295	159	5145	20	85
Spokane	9	25	168	493	879	1082	1231	980	834	531	288	135	6655	- 2	93
Stampede Pass	273	291	393	701	1008	1178	1287	1075	1085	855	654	483	9283		
Tatoosh Island	295	279	306	406	534	639	713	613	645	525	431	333	5719		
Walla Walla	0	0	87	310	681	843	986	745	589	342	177	45	4805	12	98
Yakima	0	12	144	450	828	1039	1163	868	713	435	220	69	5941	6	94
W. VA: Charleston	0	0	63	254	591	865	880	770	648	330	96	9	4476	9	92
Elkins	9	25	135	400	729	992	1008	896	791	444	198	48	5675	1	87
Huntington	0	0	63	257	585	856	880	764	636	294	99	12	4446	10	95
Parkersburg	0	0	60	264	606	905	942	826	691	339	115	6	4754	8	93
WIS: Green Bay	28	50	174	484	924	1333	1494	1313	1141	654	335	99	8029	-12	88
La Crosse	12	19	153	437	924	1339	1504	1277	1070	540	245	69	7589	-12	90
Madison	25	40	174	474	930	1330	1473	1274	1113	618	310	102	7863	- 9	92
Milwaukee	43	47	174	471	876	1252	1376	1193	1054	642	372	135	7635	- 6	90
WYO: Casper	6	16	192	524	942	1169	1290	1084	1020	657	381	129	7410	-11	92
Cheyenne	19	31	210	543	924	1101	1228	1056	1011	672	381	102	7278	- 6	89
Lander	6	19	204	555	1020	1299	1417	1145	1017	654	381	153	7870	-16	92
Sheridan	25	31	219	538	948	1200	1355	1154	1054	642	366	150	7683	-12	95

BLANK WORKSHEET FORMS

Worksheet TA-1
Sheet 1 of 2

Building Heat Load Calculations

Job ______________________________ Number of Occupants ______

Computed by ______________________ Date ______________

Location _________________________ Latitude ______________

Indoor temperature, T_R, ______________ °F

Design winter outdoor temperature, T_o. ______ °F

Design temperature difference ______________ °F

Design degree-day, 65 - T_o, ______________ °F

Building Dimensions:

Above Grade: Length ____ ft Width ____ ft Ceiling Height ____ ft

Below Grade: Length ____ ft Width ____ ft Depth __________ ft

Concrete Floor Slab: Exposed perimeter ____ ft

Exterior Wall Area: ______________________________

Window Area: ______________________________

Door Area: ______________________________

Net Exterior Wall Area: ______________________________

Ceiling Area: ______________________________

Floor Area: ______________________________

Basement Wall Area: ______________________________

Heating Degree-Days:* January ________ °F-days

Annual ________ °F-days

---

* From Table 13-2

Worksheet TA-1
Sheet 2 of 2

		U $\frac{Btu}{(hr)(ft^2)(^\circ F)}$	A	ΔT °F ($T_R - T_o$)	h = UA ΔT Btu/hr
Exterior Walls (net)					
Basement Walls	Above grade				
	Below grade			*	
Windows and Sliding Patio Doors	Single				
	Double				
	Triple				
	Storm				
Exterior Slab Doors					
Floors	Over Crawlspace				
	Concrete Slab on Grade				
	Basement				
Ceiling					
Subtotal (walls, windows, doors, floors, ceiling)					
Infiltration: (0.018) x ________ ft^3 x ________ °F					
Duct = 10% of subtotal (if ducts not in insulation envelope)					
Design Heating Load: Btu/hr					
Design Heating Load: Btu/DD Design Heating Load (Btu/hr) X (24 hr/Design TD)					
January Heating Load: m Btu (Btu/DD) X (January DD)					
Annual Heating Load: m Btu (Btu/DD) X (Annual DD)					

* $\Delta T = T_R - 45^\circ$

DOMESTIC HOT WATER LOAD

Number of occupants X 16,680 Btu/day	
January Load (m Btu) (Btu/day) x 31 x 10^{-6}	
Annual Load (m Btu) (January load x 12)	

Worksheet TA-1
Sheet 1 of 2

Building Heat Load Calculations

Job ____________________ Number of Occupants ______
Computed by ____________________ Date ______________
Location ____________________ Latitude ______________

Indoor temperature, T_R, ______________ °F
Design winter outdoor temperature, T_O. ______ °F
Design temperature difference ______________ °F
Design degree-day, 65 - T_O, ______________ °F

Building Dimensions:
Above Grade: Length _____ ft Width _____ ft Ceiling Height _____ ft
Below Grade: Length _____ ft Width _____ ft Depth ______________ ft
Concrete Floor Slab: Exposed perimeter _____ ft

Exterior Wall Area: ______________________________

Window Area: ______________________________

Door Area: ______________________________

Net Exterior Wall Area: ______________________________

Ceiling Area: ______________________________

Floor Area: ______________________________

Basement Wall Area: ______________________________

Heating Degree-Days:* January __________ °F-days
Annual __________ °F-days

* From Table 13-2

Worksheet TA-1
Sheet 2 of 2

		U Btu/(hr)(ft^2)($^\circ$F)	A	ΔT $^\circ$F (T_R - T_o)	h = UA ΔT Btu/hr
Exterior Walls (net)					
Basement Walls	Above grade				
	Below grade			*	
Windows and Sliding Patio Doors	Single				
	Double				
	Triple				
	Storm				
Exterior Slab Doors					
Floors	Over Crawlspace				
	Concrete Slab on Grade				
	Basement				
Ceiling					
Subtotal (walls, windows, doors, floors, ceiling)					
Infiltration: (0.018) x ________ ft^3 x ________ °F					
Duct = 10% of subtotal (if ducts not in insulation envelope)					
Design Heating Load: Btu/hr					
Design Heating Load: Btu/DD Design Heating Load (Btu/hr) X (24 hr/Design TD)					
January Heating Load: m Btu (Btu/DD) X (January DD)					
Annual Heating Load: m Btu (Btu/DD) X (Annual DD)					

* $\Delta T = T_R - 45^\circ$

DOMESTIC HOT WATER LOAD

Number of occupants X 16,680 Btu/day	
January Load (m Btu) (Btu/day) x 31 x 10^{-6}	
Annual Load (m Btu) (January load x 12)	

TRAINING COURSE IN
THE PRACTICAL ASPECTS OF
SIZING, INSTALLATION, AND OPERATION OF SOLAR HEATING AND COOLING SYSTEMS
FOR
RESIDENTIAL BUILDINGS

MODULE 14

SOLAR SYSTEM SIZING

SOLAR ENERGY APPLICATIONS LABORATORY
COLORADO STATE UNIVERSITY
FORT COLLINS, COLORADO

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INTRODUCTION

Solar heating systems are sized to provide a desired fraction of the total heating load of the building. The desired fraction of heating load can be chosen arbitrarily, or determined from economic analysis, so that the annual heating cost of the solar-auxiliary system is minimized. The collector area is the main quantity to be determined and, from the collector area, the storage size is selected. The size of the auxiliary furnace is based upon the design heating load and desired heat delivery rate. The appurtenant pumps, blowers, and heat exchangers depend primarily upon the collector size and heat delivery rate.

There are various methods for determining the fraction of annual heating load supplied by solar systems, varying from detailed computer programs to rules of thumb. The method described in this module is an approximate method to size solar collectors for both liquid and air-heating systems. After many computer-based designs, experiments, and several years of practical experience, several rules of thumb have been suggested. The rules of thumb are to be used as general guidelines, and manufacturers of components and solar systems may have more detailed information and specific recommendations.

OBJECTIVE

This module is directed to sizing of solar heating systems for residential buildings. From this module the trainee should be able to determine the approximate fraction of the annual heating load which a solar heating system will deliver to a given building.

RULES OF THUMB

Rules of thumb for sizing air and hydronic solar systems are presented in Table 14-1. Collector area is not listed in the table because there is considerable variation and freedom to choose areas arbitrarily. From the collector area sizes, other components of the system may be determined.

Table 14-1

Rules of Thumb for Sizing

SOLAR AIR HEATING SYSTEMS	
Collector slope	Latitude + 15°
Collector air flow rate	1.5 to 2 cfm/ft^2 of collector
Pebble-bed storage size	1/2 to 1 ft^3 of rock/ft^2 of collector
Rock depth	4 to 8 feet in air flow direction
Pebble size	3/4" to 1" concrete aggregate
Duct insulation	1" fiberglass minimum
Pressure drops:	
Pebble-bed	0.1 to 0.3" W.G.
Collector (12-14 ft lengths)	0.2 to 0.3" W.G.
Collector (18-20 ft lengths)	0.3 to 0.5" W.G.
Ductwork	∿0.08" W.G./100' duct length
SOLAR HYDRONIC HEATING/COOLING SYSTEMS	
Collector slope	Latitude + 15°
Collector flow rate	∿0.02 gpm/ft^2 of collector
Water storage size	1.5 to 2.5 gallons/ft^2 of collector
Pressure drop across collector	0.5 to 10 psi/collector module
SOLAR DOMESTIC HOT WATER HEATING SYSTEMS	
Preheat tank size	1.5 to 2.0 times DHW auxiliary tank size

FRACTION OF THE ANNUAL HEATING LOAD CARRIED BY A SOLAR HEATING SYSTEM

The collector area required for hydronic and air heating solar systems to provide the desired fraction of the annual heating load is determined by the use of Figure 14-1. The symbols used in the figure are; A, the solar collector area in square feet (ft^2); L, the January heating load of the building in Btu per month; S, the total solar radiation per unit area for the month of January on a horizontal surface at the building location in Btu/(ft^2)(month); and f, the fraction of the annual heating load delivered by the solar heating system. Suppose that a solar heating system has a total collector area of 500 square feet, the building has a heating load in January of 15 million Btu, and the total solar radiation in January at the location is 31,000 Btu/ft^2. Then,

$$\frac{AS}{L} = \frac{31,000 \times 500}{15,000,000} = 1.0.$$

From Figure 14-1, it is seen that a liquid-heating solar system would provide about 80 percent of the annual heating load and an air-heating system would provide about 90 percent of the annual load.

For the purpose of sizing the area of collectors in a system, the values of S and L are determined for the particular building at a given location, and the fraction of the annual heating load, f, is selected. With these values, the area of collectors needed to provide the desired fraction of annual heating load is determined with the aid of Figure 14-1. For example, let us suppose that we desire a solar hydronic system to supply 80 percent of the annual load. From Figure 14[illegible] the value of AS/L corresponding to f of 0.8 is 0.9. Thus,

$$\frac{AS}{L} = 0.9$$

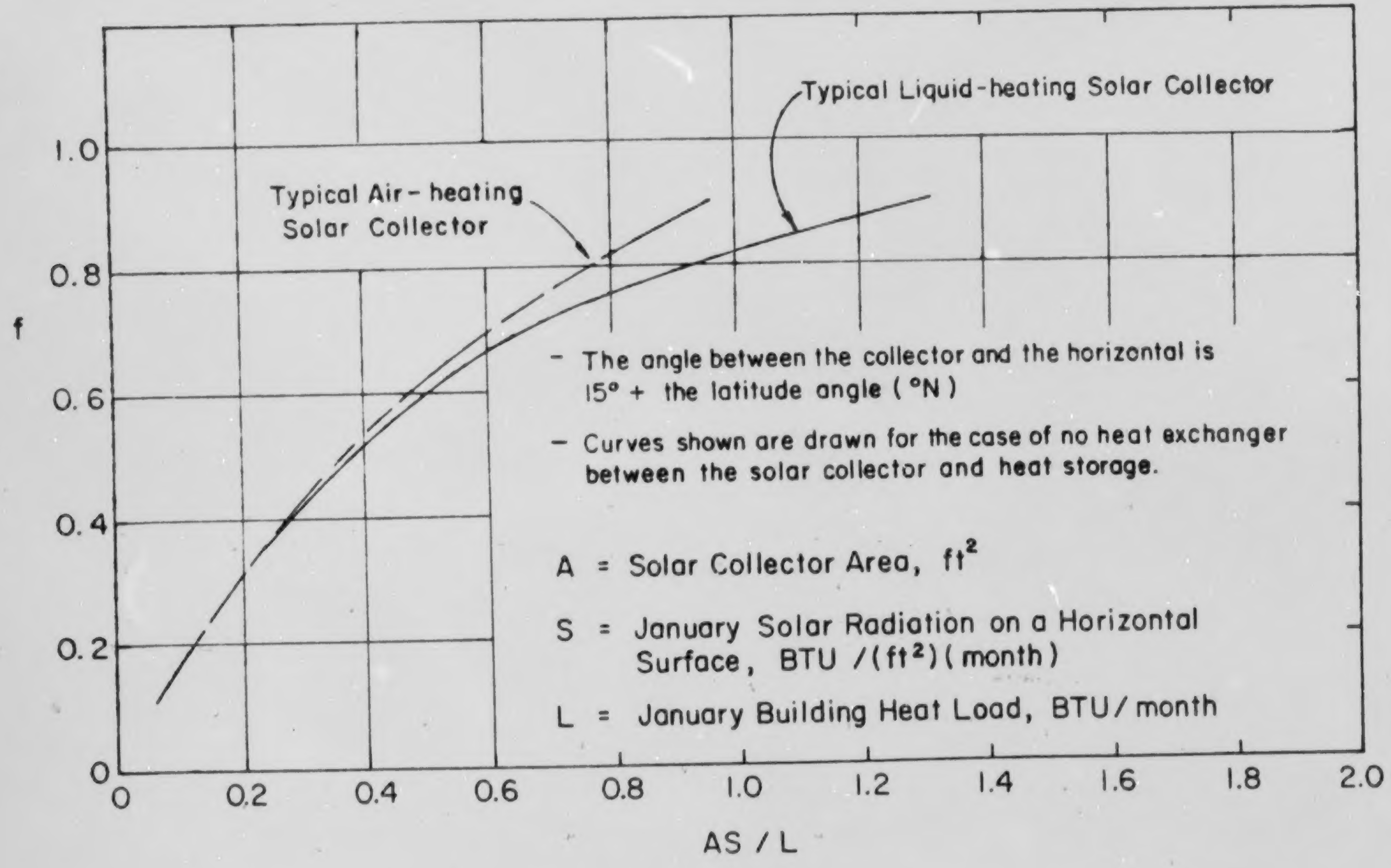

Figure 14-1. Fraction of Annual Heating Load Furnished by a Solar Heating System

and the area of collectors needed is determined by:

$$A = \frac{0.9 \times L}{S} .$$

The area of collector desired is dependent upon the January solar radiation, S, and January heating load, L, of the building. The mean daily radiation for January (also for every month of the year) is listed for several cities in Table 4-1 (see Module 4). The cities listed in the table are limited in number and, for other locations, the maps of Figures 4-9 or 4-20 may be used. The values in the table, or those obtained by interpolation from the maps, must be multiplied by 31, the number of days in January, to establish the value S. The January heating load for the building is determined from the procedures described in Module 13.

Because it is not practical to design a solar system to provide more than 90 percent of the annual load for a building, the curves in Figure 14-1 do not apply for f greater than 0.9. There are several assumptions concerning the "typical" solar systems used in determining the curves in Figure 14-1. The "typical" flat-plate collectors consist of two glass covers and an absorber coated with black paint. A "typical" air-heating collector consists of two glass covers and black absorber, and the air flows through a duct beneath the absorber plate. In a "typical" liquid heating collector, the liquid flows through tubes that are either integral with, or bonded to, the absorber plate. The collectors for the typical systems are facing due south and tilted at an angle equal to the latitude plus 15 degrees. It is also assumed that the hydronic system has no heat exchanger between the collector loop and the storage circulation loop. When there are variations in the systems from these assumptions, corrections must be applied to determine the appropriate collector area.

EFFECT OF HEAT EXCHANGERS

For liquid-heating solar systems in cold climates a heat exchanger between the solar collector and the hot water storage tank is appropriate. The effect of a heat exchanger is to reduce the temperature of the water in storage because a finite temperature difference is required to transfer the heat from the collector fluid to the storage fluid across the heat exchanger. Alternatively, we may consider that the heat exchanger raises the operating temperature of the fluid in the collector to provide the required storage water temperature. The warmer collector fluid temperature causes a reduction in collector efficiency, which reduces the quantity of heat delivered to storage.

The effect of the heat exchanger may be offset by increasing the area of the collectors. The additional collector area required is one percent for every one °F across the heat exchanger. A well-designed heat exchanger will operate with a temperature difference of about 10°F between the collector and storage water loops. The collector area calculated with the use of Figure 14-1 should then be increased by 10 percent. If the temperature difference is 15°F, the area should be increased by 15 percent.

An air-heating solar system does not require a heat exchanger because the air which is heated in the collectors is delivered directly to the rooms or passed through storage where heat is transferred to the pebble-bed. The surface of the storage material is, in effect, also the heat exchanger. When no heat exchanger is used in a hydronic system between the collector and storage loops, a correction need not be applied to the collector area determined from Figure 14-1.

EFFECT OF COLLECTOR TILT

The recommended angle between the plane of solar collectors and the horizontal is 15 degrees plus the local latitude, ℓ (°N) for the systems represented in Figure 14-1. As an example, if the location is Boulder, Colorado, where the latitude is 40°, the collectors are tilted 55° (40 + 15) from the horizontal and facing southward. The effect of solar collectors mounted at tilt angles other than that recommended is shown in Figure 14-2. Continuing with Boulder, Colorado, as an example, suppose the collectors are tilted 25° from the horizontal (ℓ - 15°); then a fixed collector area will deliver only 90 percent of the energy that the same collector area will deliver when tilted at 55°. If the same fraction of the annual heating load is to be provided, the collector area must be 11 percent greater [(100% : 0.9) - 100%] for collectors placed at a 25° tilt angle.

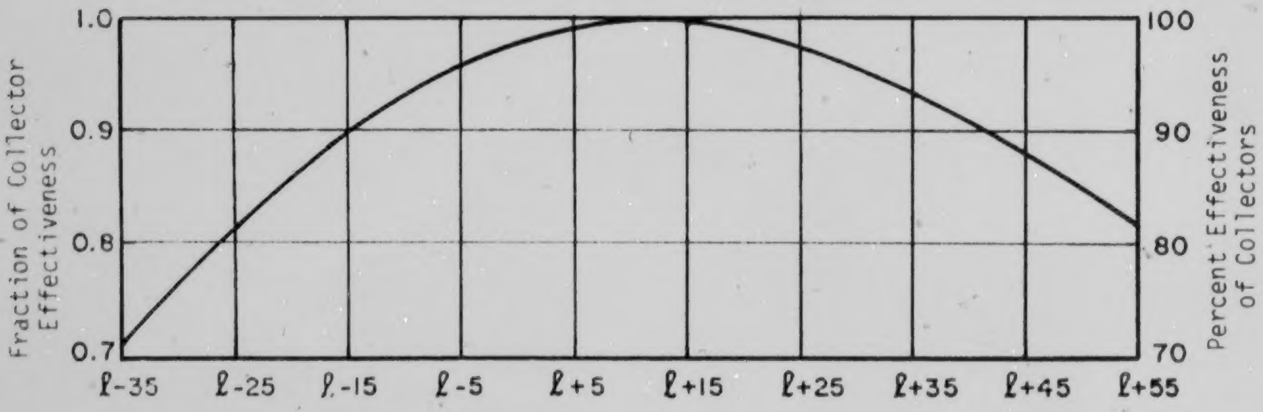

Figure 14-2. Effect of Solar Collector Tilt on Annual Heating Performance [ℓ = local latitude (°N)]

EFFECT OF ORIENTATION

Figure 14-1 applies to collectors facing due south. The effect of solar collector orientation on annual heating performance is shown in Figure 14-3. There is reduction in the amount of heat delivered by collectors that are not facing due south. For example, if the solar collectors of a given system face southeast (45° east of south), then the system would deliver only 90 percent of the heat provided with a south-facing collector. The collector area should therefore be increased by 11 percent in order to provide the same fraction of the annual heating load of the building.

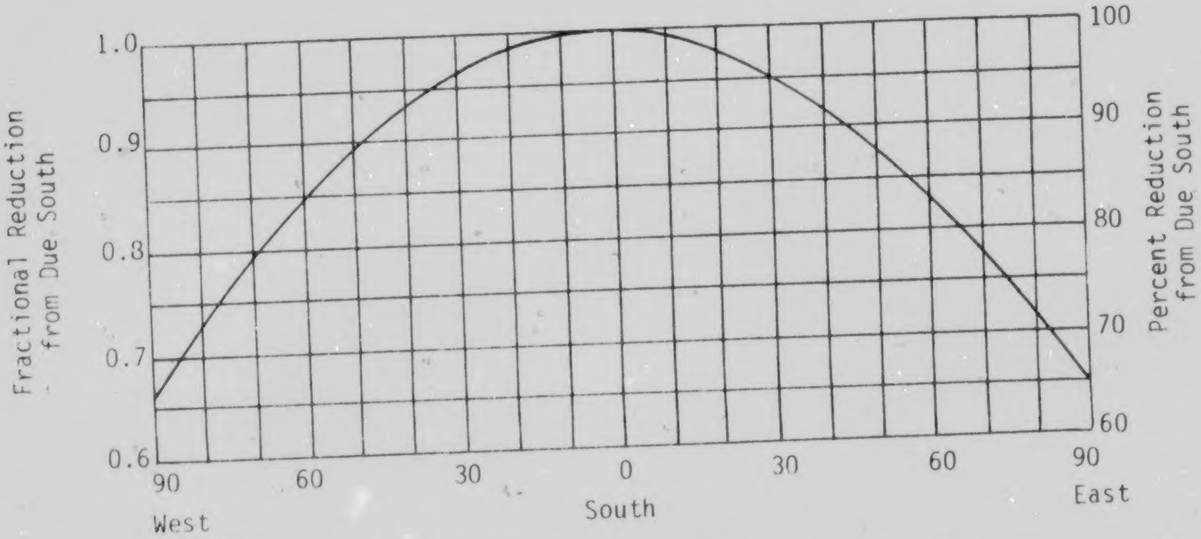

Figure 14-3. Effect of Solar Collector Orientation on Annual Heating Performance

WORKSHEET TA-2

Collector Area

The calculations needed to determine the collector area for a preselected fraction of the annual heating load are organized on worksheet TA-2.

A. The latitude, (ℓ), of the solar system installation is needed to set the collector tilt. If the latitude is not known, the map of Figure 4-20 (Module 4) may be used to determine approximate latitude.

B. The mean daily solar radiation in January, (s), for selected cities is listed in Table 4-4 in Module 4. Values are in Langleys and should be multiplied by 3.69 to convert the units to Btu/ft^2·day. If the values in Table 4-1 are inappropriate, Figure 4-20 may be used. It will be necessary to interpolate between the iso-radiation intensity lines.

C. Average radiation for the month of January, (S), is determined by multiplying the value in B by 31, the number of days in January.

D. The building heat load for January is calculated on worksheet TA-1.

E. Divide item C by item D. This yields the quantity S/L.

F. Enter collector tilt. The recommended collector tilt is latitude plus 15 degrees for heating systems.

G. Collectors oriented due south is zero. Off-south angles east or west of south should be indicated.

H. Indicate whether a heat exchanger is used.

I. Calculate collector area as follows:

Column [1], enter trial number. Note: Trial collector sizes will be used in the life cycle cost analysis to determine best collector size.

Worksheet TA-2

SOLAR SYSTEM DATA

Building Owner: ______________________
Address: ______________________
Contractor: ______________________
Type of Solar System (air or liquid) ____________

A. Location: Nearest city ______________ Latitude (ℓ) ________

B. Mean daily solar radiation in January (s) __________ (Btu/ft^2·day)

C. January solar radiation on a horizontal surface (S)
(B x 31) = __________ (Btu/ft^2·month)

D. January building heat load (L) ______________ (Btu/month)

E. January solar radiation ÷ January building load
(S ÷ L) = __________ (1/ft^2)

F. Collector tilt ________: ℓ + ______ or ℓ - ______

G. Collector Orientation ________ degrees, __________ from south

H. Heat Exchanger Temperature Difference (Liquid systems only) ______ °F

I. Fraction of annual heating load:

[1] Trial Number	[2] Trial Collector Area at Tilt = Latitude A	[3] Area Corrected for Tilt A	[4] Area Corrected for Orientation A	[5] Area Corrected for Heat Exchanger A	[6] $\frac{SA}{L}$	[7] f

[2] Selected arbitrarily or determined from f
[3] Correction to column [2] for tilt not equal to latitude + 15° (Fig. 14-2)
[4] Correction to column [3] for orientation (Fig. 14-3)
[5] Correction to column [4] for heat exchanger (liquid systems only)
[6] From Figure 14-1
[7] Selected arbitrarily or determined from Figure 14-1

Column [7], enter fraction of load to be carried by solar.

Column [6], enter the value from Figure 14-1 for the liquid or air system.

Column [2], calculate area from

A = value in column [6] ÷ item E

Column [3], correct area for flatter or steeper tilt than ℓ + 15 using factor from Figure 14-2. Divide A in column [2] by factor from Figure 14-2.

Column [4], correct area for orientation. Divide A in column [3] by factor from Figure 14-3.

Column [5], correct area for heat exchanger. Multiply A in column [4] by [1 + (temperature difference in H/100)], i.e., $[1 + \frac{10}{100}]$ for a 10 degree temperature difference at the heat exchanger. NOTE: This applies to liquid systems only.

Fraction of Annual Load

The calculations to determine the fraction of annual load can also be made by using worksheet TA-2.

Items A through H are provided in the same manner as previously described.

I. Calculate fraction of annual load as follows:

Column [1], enter trial number. Note: Trial collector sizes will be used in the life cycle cost analysis to determine best collector size.

Column [2], enter trial collector area.

Column [3], correct area for tilt.

Divide column [2] by factor from Figure 14-2.

Column [4], correct area for orientation.

Divide column [3] by factor from Figure 14-3.

Column [5], correct area for heat exchanger.

Multiply column [4] by $\left(1 + \frac{\text{temperature difference}}{100}\right)$

Note: This applies to liquid systems only.

Column [6], calculate SA/L.

Multiply A in column [2] by S/L in item E of the worksheet.

Column [7], read f from Figure 14-1 for air or liquid solar system.

Extra worksheets are provided at the end of this module. Copies should be made from the blank forms for general office use.

EXAMPLE

A building in Boston, Massachusetts, has a January heating load of 27.85 million Btu per month and an annual heating load, H, of 154.08 million Btu per year. An air-heating solar system is planned.

The collector is to be tilted at an angle of 83 degrees from the horizontal and faces 35 degrees west of south. Determine the solar collector area required to provide 60 percent of the annual heating load. The solution is given on worksheet TA-2.

From worksheet TA-2, the area required is 1060 ft^2. If the collector modules are 3 feet by 6 feet, then the total number of collector modules required is:

$$N = \frac{1060\ ft^2}{18\ ft^2/module} = 58.9\ modules$$

Because integer, and usually even numbers of modules are desired, 60 collector modules will probably be used.

SOLAR SYSTEM SIZING

When the collector area has been determined, the other system components may be selected. Worksheet TA-3 is provided for convenience. Most of the sizing guidelines are provided in Table 14-1, except for sizes of pumps, blowers and heat exchangers. The selection of heat exchangers may require specialized assistance. Manufacturer's representatives or catalogs can be used as aids in making proper selections.

Worksheet TA-2

SOLAR SYSTEM DATA

Building Owner: ______________________

Address: ______________________

Contractor: ______________________

Type of Solar System (air or liquid) Air

A. Location: Nearest city Boston, MA Latitude (ℓ) 42

B. Mean daily solar radiation in January (s) = 476 (Btu/ft^2·day)

C. January solar radiation on a horizontal surface (S) (B x 31) = 14,756 (Btu/ft^2·month)

D. January building heat load (L) 27,850,000 (Btu/month)

E. January solar radiation ÷ January building load (S ÷ L) = 0.00053 (1/ft^2)

F. Collector tilt 83° : ℓ + 41 or ℓ - ______

G. Collector Orientation 35 degrees, West from south

H. Heat Exchanger Temperature Difference (Liquid systems only) 0 °F

I. Fraction of annual heating load:

[1]	[2]	[3]	[4]	[5]	[6]	[7]
Trial Number	Trial Collector Area at Tilt = Latitude A	Area Corrected for Tilt A	Area Corrected for Orientation A	Area Corrected for Heat Exchanger A	$\frac{SA}{L}$	f
1	906	1006	1060	—	0.48	.60

[2] Selected arbitrarily or determined from f

[3] Correction to column [2] for tilt not equal to latitude + 15° (Fig. 4-2)

[4] Correction to column [3] for orientation (Fig. 14-3)

[5] Correction to column [4] for heat exchanger (liquid systems only)

[6] From Figure 14-1

[7] Selected arbitrarily or determined from Figure 14-1

WORKSHEET TA-3

SOLAR SYSTEM SIZE

A. Type of System ____________

B. Economical Collector Area ____________ ft^2

C. Collector Tilt ____________ degrees

D. Collector Fluid Flow Rate:

1. Air System (1.5 to 2 cfm/ft^2 collector) ____________ cfm
2. Liquid System (0.02 gpm/ft^2 collector) ____________ gpm

E. Pumps: Liquid System

1. Collector loop flow rate (D.2) ____________ gpm
   Head ____________ ft
2. Storage loop flow rate (1.5 x E.1) ____________ gpm
   Head ____________ ft
3. Service water preheater ___3___ gpm
   Head ___2-3___ ft
4. Heat distribution coil (depends upon heat delivery rate) ____________ gpm
   Head ____________ ft

F. Blowers: Air System

1. Collector loop (D.1) ____________ cfm
   Head ___1-1.5___ in w.g.
2. Distribution blower (provided with furnace) ____________ cfm
   Head ____________ in w.g.
3. One blower system (D.1) ____________ cfm
   Head ___1-1.5___ in w.g.

G. Storage:

1. Liquid system B x 2.0 $gallons/ft^2$ collector ____________ gal
2. Air system B x 1/2 ft^3/ft^2 collector ____________ ft^3
   (a) Pebble size (1-in. screened concrete aggregate)
   (b) Cross-section area (D.1 ÷ 20) ____________ ft^2
   (c) Rock depth (G.2 ÷ G.2.b) ____________ ft

H. Heat Exchangers:

Consult heat exchanger manufacturer

REFERENCES

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2. Solaron Corporation, "Application Engineering Manual", 1976.

3. Balcomb, J.D., Hedstrom, J.C., and Rogers, B.T., "Design Considerations of Air Cooled Collector/Rock-Bin Storage Solar Heating Systems". Presented at the 1975 International Solar Energy Society Congress, University of California, Los Angeles, CA, July 28-August 1, 1975.

BLANK WORKSHEET FORMS

Worksheet TA-2

SOLAR SYSTEM DATA

Building Owner: ______________________________

Address: ______________________________

Contractor: ______________________________

Type of Solar System (air or liquid) ____________

A. Location: Nearest city __________________ Latitude (ℓ) ________

B. Mean daily solar radiation in January (s) ____________ (Btu/ft^2·day)

C. January solar radiation on a horizontal surface (S)
(B x 31) = ____________ (Btu/ft^2·month)

D. January building heat load (L) ______________ (Btu/month)

E. January solar radiation : January building load
(S : L) = ____________ (1/ft^2)

F. Collector tilt ________ : ℓ + _______ or ℓ - _______

G. Collector Orientation _________ degrees, ____________ from south

H. Heat Exchanger Temperature Difference (Liquid systems only) _____ ^{o}F

I. Fraction of annual heating load:

[1] Trial Number	[2] Trial Collector Area at Tilt = Latitude A	[3] Area Corrected for Tilt A	[4] Area Corrected for Orientation A	[5] Area Corrected for Heat Exchanger A	[6] $\frac{SA}{L}$	[7] f

[2] Selected arbitrarily or determined from f

[3] Correction to column [2] for tilt not equal to latitude + 15^{o} (Fig. 14-2)

[4] Correction to column [3] for orientation (Fig. 14-3)

[5] Correction to column [4] for heat exchanger (liquid systems only)

[6] From Figure 14-1

[7] Selected arbitrarily or determined from Figure 14-1

Worksheet TA-2

SOLAR SYSTEM DATA

Building Owner: ______________________________

Address: ______________________________

Contractor: ______________________________

Type of Solar System (air or liquid) __________

A. Location: Nearest city ______________ Latitude (ℓ) ________

B. Mean daily solar radiation in January (s) __________ (Btu/ft^2·day)

C. January solar radiation on a horizontal surface (S)
(B x 31) = __________ (Btu/ft^2·month)

D. January building heat load (L) __________ (Btu/month)

E. January solar radiation : January building load
(S : L) = __________ (1/ft^2)

F. Collector tilt ________ : ℓ + ________ or ℓ - ________

G. Collector Orientation ________ degrees, __________ from south

H. Heat Exchanger Temperature Difference (Liquid systems only) ______ °F

I. Fraction of annual heating load:

[1] Trial Number	[2] Trial Collector Area at Tilt = Latitude A	[3] Area Corrected for Tilt A	[4] Area Corrected for Orientation A	[5] Area Corrected for Heat Exchanger A	[6] $\frac{SA}{L}$	[7] f

[2] Selected arbitrarily or determined from f

[3] Correction to column [2] for tilt not equal to latitude + 15° (Fig. 14-2)

[4] Correction to column [3] for orientation (Fig. 14-3)

[5] Correction to column [4] for heat exchanger (liquid systems only)

[6] From Figure 14-1

[7] Selected arbitrarily or determined from Figure 14-1

WORKSHEET TA-3

SOLAR SYSTEM SIZE

A. Type of System ____________

B. Economical Collector Area ____________ ft^2

C. Collector Tilt ____________ degrees

D. Collector Fluid Flow Rate:

1. Air System (1.5 to 2 cfm/ft^2 collector) ____________ cfm
2. Liquid System (0.02 gpm/ft^2 collector) ____________ gpm

E. Pumps: Liquid System

1. Collector loop flow rate (D.2) ____________ gpm
   Head ____________ ft
2. Storage loop flow rate (1.5 x E.1) ____________ gpm
   Head ____________ ft
3. Service water preheater ____3____ gpm
   Head ____2-3____ ft
4. Heat distribution coil (depends upon heat delivery rate) ____________ gpm
   Head ____________ ft

F. Blowers: Air System

1. Collector loop (D.1) ____________ cfm
   Head ____1-1.5____ in w.g.
2. Distribution blower (provided with furnace) ____________ cfm
   Head ____________ in w.g.
3. One blower system (D.1) ____________ cfm
   Head ____1-1.5____ in w.g.

G. Storage:

1. Liquid system B x 2.0 gallons/ft^2 collector ____________ gal
2. Air system B x 1/2 ft^3/ft^2 collector ____________ ft^3
   (a) Pebble size (1-in. screened concrete aggregate)
   (b) Cross-section area (D.1 : 20) ____________ ft^2
   (c) Rock depth (G.2 : G.2.b) ____________ ft

H. Heat Exchangers:

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WORKSHEET TA-3

SOLAR SYSTEM SIZE

A. Type of System ______

B. Economical Collector Area ______ ft^2

C. Collector Tilt ______ degrees

D. Collector Fluid Flow Rate:

1. Air System (1.5 to 2 cfm/ft^2 collector) ______ cfm
2. Liquid System (0.02 gpm/ft^2 collector) ______ gpm

E. Pumps: Liquid System

1. Collector loop flow rate (D.2) ______ gpm
   Head ______ ft
2. Storage loop flow rate (1.5 x E.1) ______ gpm
   Head ______ ft
3. Service water preheater 3 gpm
   Head 2-3 ft
4. Heat distribution coil (depends upon heat delivery rate) ______ gpm
   Head ______ ft

F. Blowers: Air System

1. Collector loop (D.1) ______ cfm
   Head 1-1.5 in w.g.
2. Distribution blower (provided with furnace) ______ cfm
   Head ______ in w.g.
3. One blower system (D.1) ______ cfm
   Head 1-1.5 in w.g.

G. Storage:

1. Liquid system B x 2.0 gallons/ft^2 collector ______ gal
2. Air system B x 1/2 ft^3/ft^2 collector ______ ft^3
   (a) Pebble size (1-in. screened concrete aggregate)
   (b) Cross-section area (D.1 : 20) ______ ft^2
   (c) Rock depth (G.2 : G.2.b) ______ ft

H. Heat Exchangers:

Consult heat exchanger manufacturer

TRAINING COURSE IN

THE PRACTICAL ASPECTS OF

SIZING, INSTALLATION, AND OPERATION OF SOLAR HEATING AND COOLING SYSTEMS

FOR

RESIDENTIAL BUILDINGS

MODULE 15

SYSTEM ECONOMICS

SOLAR ENERGY APPLICATIONS LABORATORY
COLORADO STATE UNIVERSITY
FORT COLLINS, COLORADO

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INTRODUCTION

The major portion of the cost of heating a house with a conventional heating system is the cost of energy used by the system. A significant portion of the cost of heating a house with a solar system includes payment for solar hardware as well as energy used by the auxiliary unit in the solar system. While the capital investment in a conventional heating system is usually less than $2,000, the capital investment in a solar heating system is many times that amount.

An economic analysis of solar systems involves comparison of the capital and operating costs of a solar system with the operating costs of a conventional system. Among the many methods available, the method of life-cycle cost is explained in this module. In this method, the annual cash flows for solar and non-solar systems are considered. If the cumulative difference in cash flows (non-solar minus solar) is positive over the life of the solar system, then the solar system is economically viable.

OBJECTIVE

The objective of this module is to describe the life-cycle cost method of economic analysis to compare solar and non-solar systems. The trainee should be able to use the work-sheets provided in this module to:

1. Determine the annual cash flows for solar and non-solar systems,
2. Determine the feasibility of a solar system,
3. Optimize the collector area for a particular solar system installation.

ENERGY COSTS

The conversion of unit costs of energy to dollars per million Btu ($/mBtu) with various furnace efficiencies is shown on Figure 15-1 for natural gas, propane, and No. 2 fuel oil. The conversion of electric energy costs to dollars per million Btu for resistance heating and heat pumps with various coefficients of performance are shown on Figure 15-2. To determine the cost per million Btu of heat generated from furnaces, electric resistance heaters, or heat pumps, follow the unit cost of energy, found on the horizontal axis of the graphs, vertically to the appropriate line on the graph and read the cost in dollars along the vertical axis. For example, if No. 2 fuel oil costs fifty cents per gallon, and the furnace efficiency is 60 percent, the energy cost is $6.00/mBtu or 60 cents per therm (¢/therm). If the furnace is more efficient, say 70 percent, the energy cost is $5.10/mBtu or 51 ¢/therm. Similarly, if electricity costs three cents per kilowatt-hour (¢/kWh), and resistance heating is used, the energy cost is $8.80/mBtu. If a heat pump is used, and the COP of the heat pump is 2, the energy cost is $4.40/mBtu.

The cost of energy will increase in future years and an estimate of the rate of increase is subject not only to inflation rates of goods and services, but also to economic and political decisions of the federal government and the governments of other nations. One expects, therefore, the rate of fuel cost increases to be different from "normal" inflation rates.

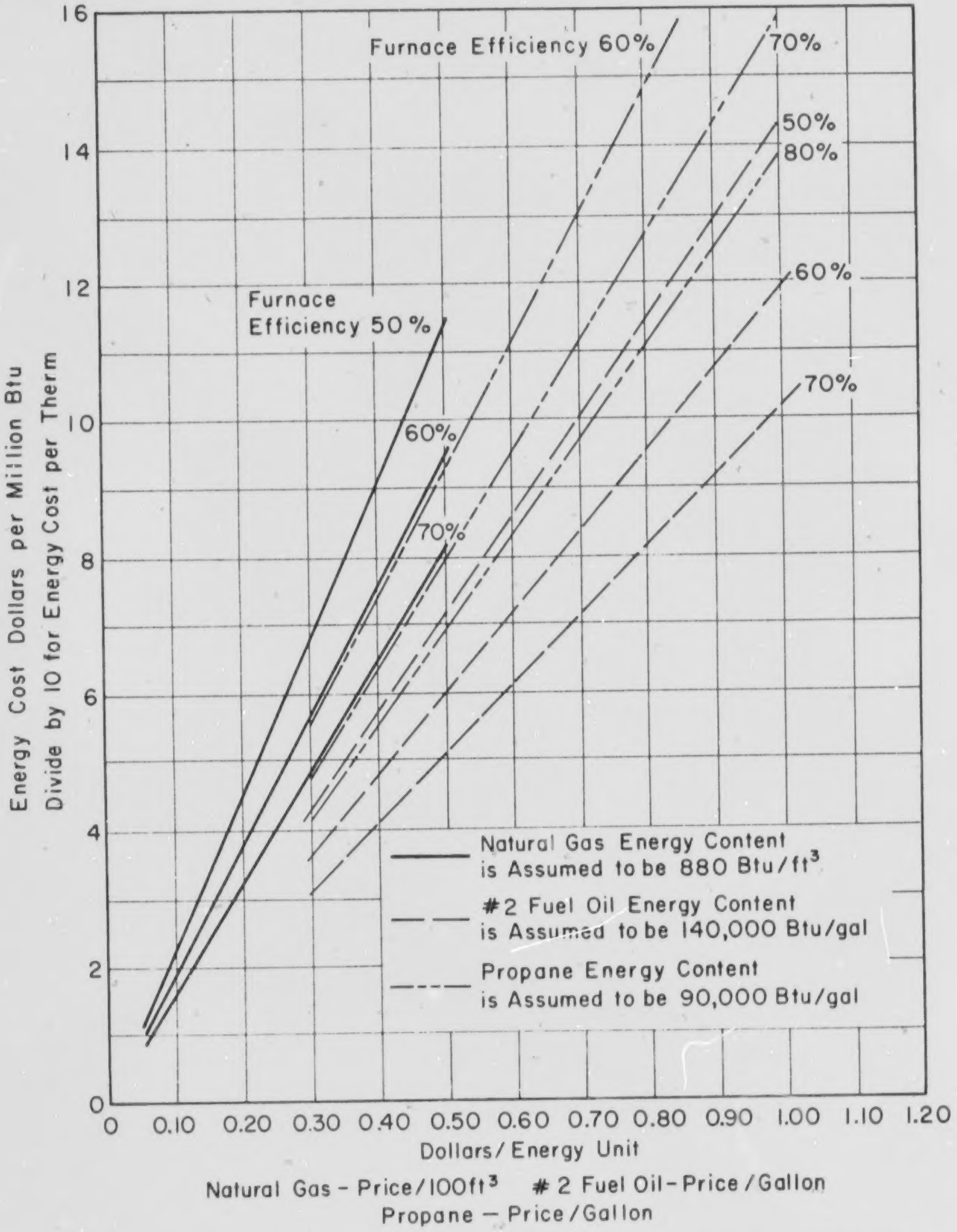

Figure 15-1. Energy Cost per Million Btu for Natural Gas, Propane and No. 2 Fuel Oil.

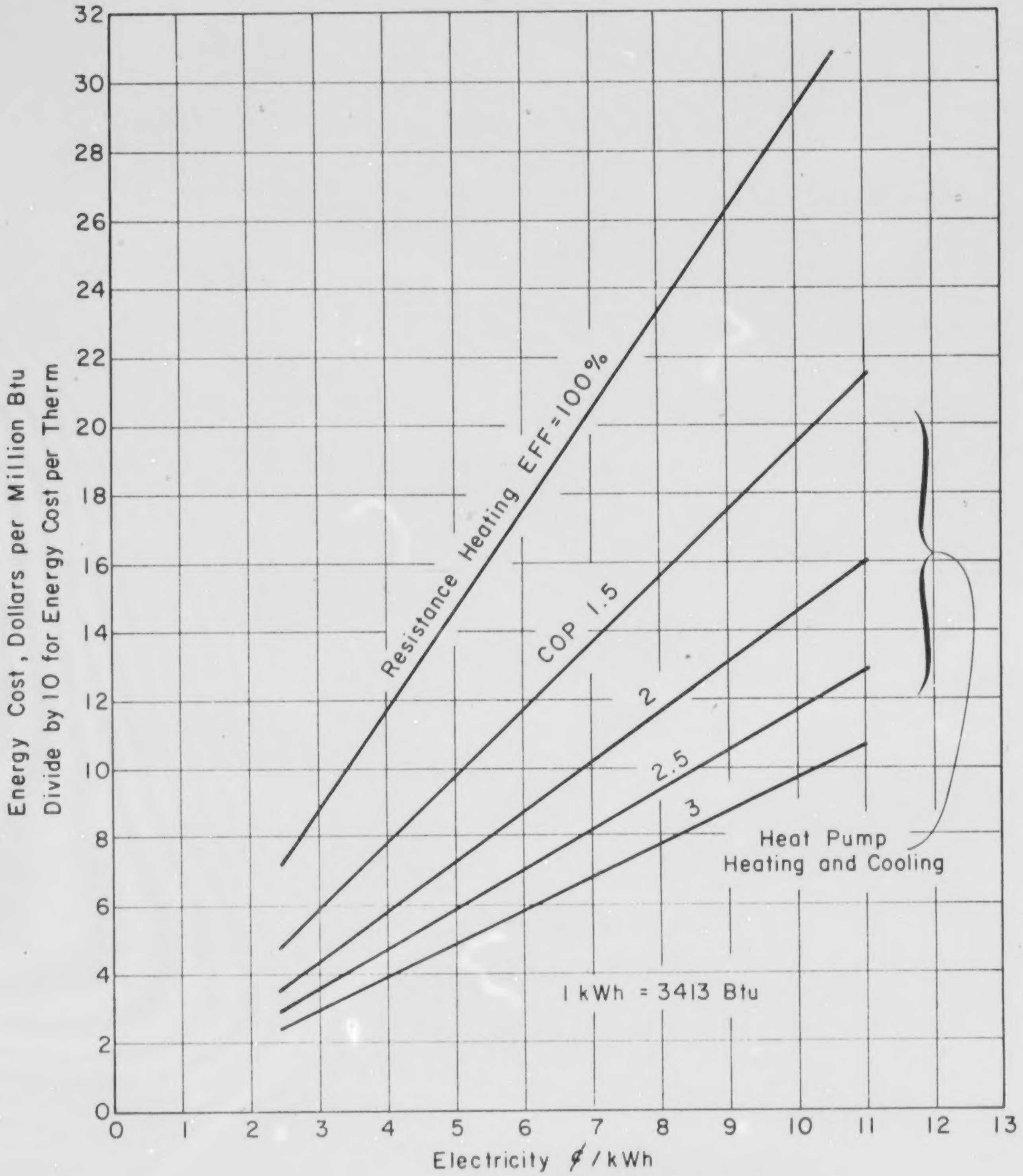

Figure 15-2. Energy Cost per Million Btu for Electricity

INFLATION RATES

The increases in costs per unit of energy, several years in the future, in terms of cents per gallon, cents per kilowatt-hour, cents per hundred cubic feet of natural gas, or dollars per therm, can be estimated on the basis of annual percentage increases over current costs. The multiplying factors for current energy costs to determine future costs is shown on Figure 15-3. The horizontal axis is the years beyond the current year. The vertical axis gives the multiplying factor over current costs.

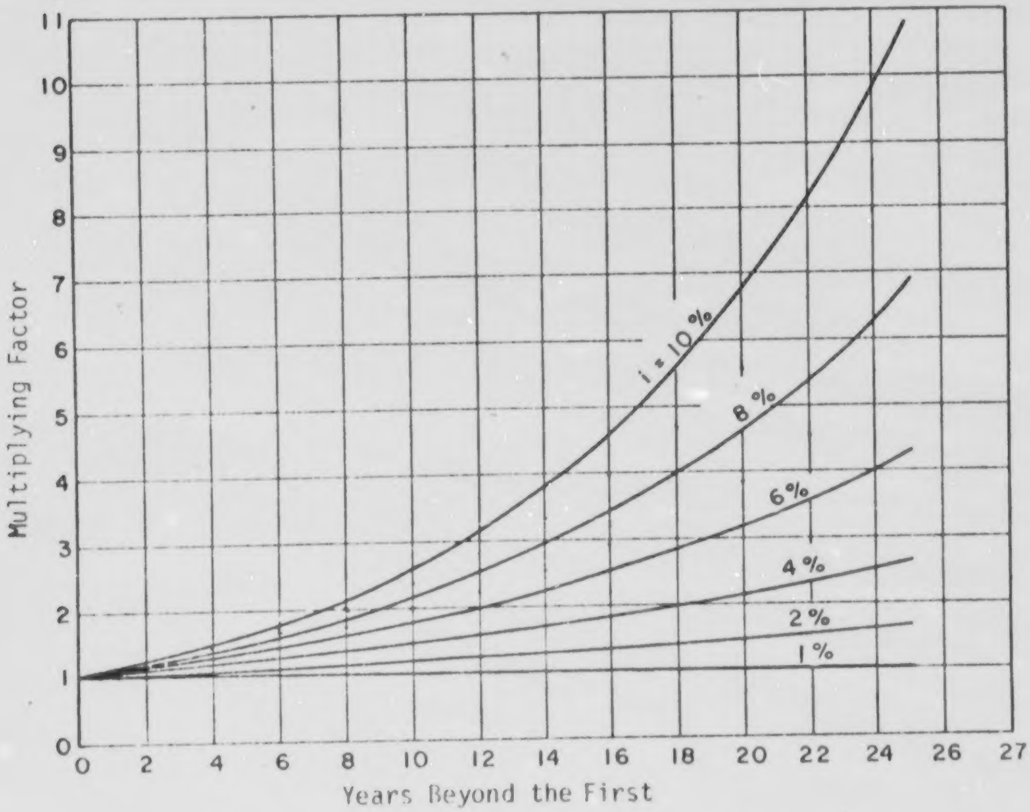

Figure 15-3. Inflation Factors

For example, if the current cost of electricity is expected to increase at a rate of 6 percent each year for the next 12 years, at the end of 12 years the electricity cost will double. If 3 cents per kilowatt-hour is the current cost and heating cost is $8.80 per million Btu, at the end of 12 years the electricity will cost 6 cents per kilowatt-hour and $17.80 per million Btu.

SOLAR SYSTEM COSTS

There is much speculation about the installed costs of complete solar systems and there is little information available to substantiate published information on costs. System costs based on research projects and demonstration projects funded by the federal government are misleading because the total costs of such projects include considerable engineering design costs, research staff costs, in some instances instrument costs for monitoring the performance of experimental systems; and often development costs of several alternative components in the systems are included. The costs reported in popular magazines and newspaper accounts are likewise misleading because often systems which are designed and assembled by the owner on a do-it-yourself basis are cited and cost for the owner's time is seldom included in the cost quotations.

On the basis of a few commercial solar installations made, where no governmental subsidy has been involved, the installed costs of practical solar space and hot water heating systems of the types discussed in this course range from 19 to about 30 dollars per square foot. The lower cost is appropriate for simple hydronic and air systems, ranging in size from 500 to 1000 square feet of collectors, where some economy of scale is realized over small systems and where experienced installers and timely scheduling are arranged with the building construction. The higher costs are appropriate for smaller systems and difficult installations.

The costs for collectors currently (1976) range from 7 to about 15 dollars per square foot, F.O.B. the job site, with more efficient collectors being generally more expensive. Storage will add one to two dollars per square foot of collector to the system costs, and appurtenances, from 5 to 8 dollars per square foot. Including the cost for experienced labor for installation, overhead, and profit of 6 to 8 dollars per square foot, the installed system costs range from 19 to 33 dollars per square foot of collector, with an average cost of about 25 dollars per square foot.

MORTGAGE PAYMENTS

The largest portion of the annual cost of a solar system is the repayment of the loan obtained to install the system. The loan may be based on the total building costs or separately on the solar system alone. In either event, a down payment ranging from 10 to 20 percent is required to secure the loan. The annual mortgage payments can be calculated from the mortgage interest rate and term of the loan using the curves of Figure 15-4.

To illustrate the use of Figure 15-4, suppose that a solar system with 500 square feet of collectors costs \$12,500 (determined by 500 ft^2 X \$25/ft^2). A 20-year loan is obtained to purchase and install the system with interest at 9 percent, which requires a 20 percent down payment. The annual mortgage payment on the loan is calculated as:

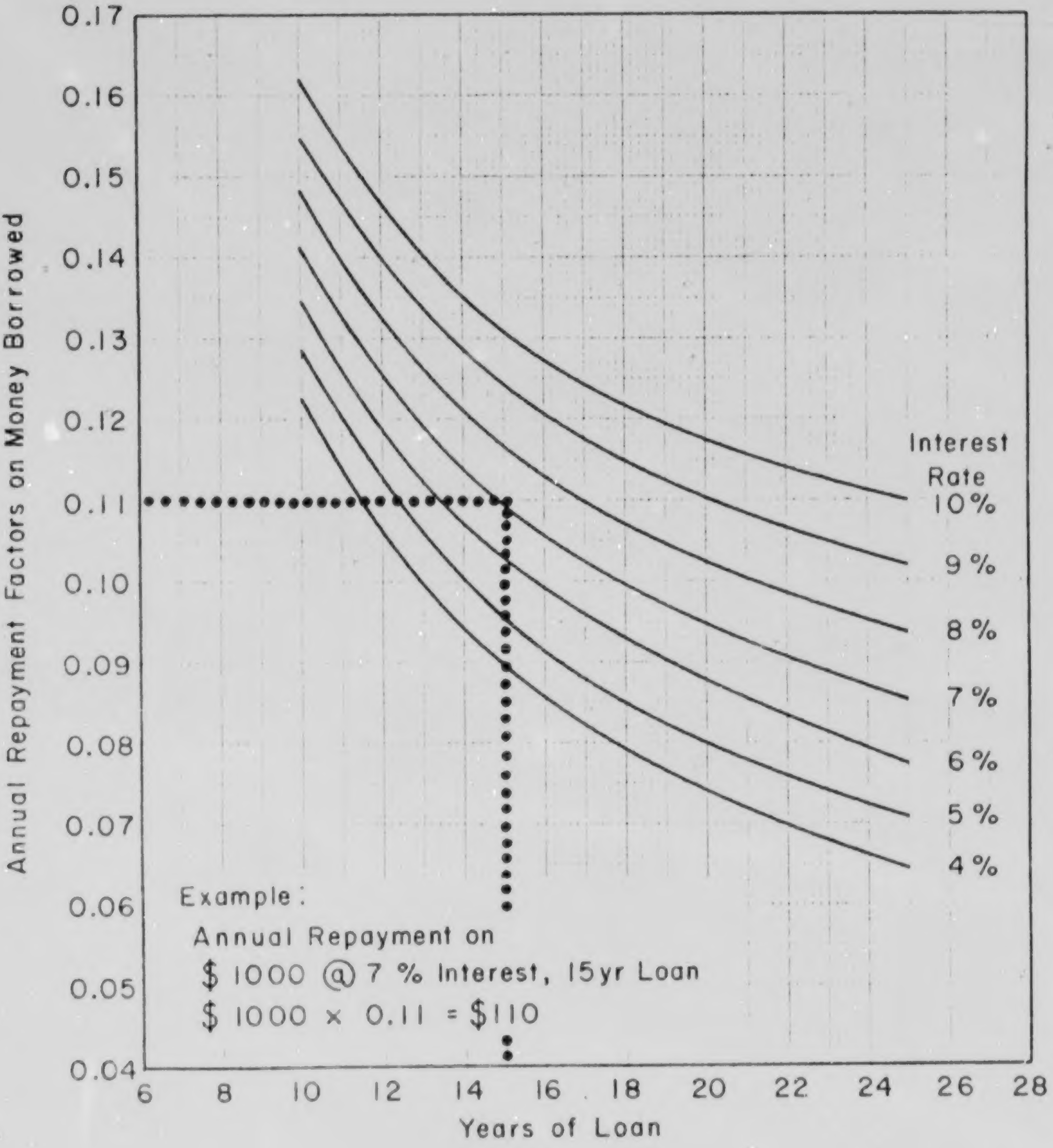

Figure 15-4. Repayment on Loan

$$\text{Annual Mortgage Payment} = (\text{System cost} - \text{down payment}) \times (\text{Annual repayment factor [from Figure 15-4]})$$

or,

$$\$1100 = (12{,}500 - 2500) \times (0.11)$$

PROPERTY TAX, INSURANCE AND CREDIT ON INCOME TAXES

The annual cost of a solar system includes all the items contributing to the cash flow to operate a solar heating system. The costs include the mortgage payment and fuel costs, operating and maintenance costs, property tax, insurance on the solar system, and savings on federal and state income taxes for interest paid on the loan. In some states there are additional credits provided to state income taxes for owners of solar systems. Some of these special tax credits are substantial and impact significantly on the annual costs of the solar system.

Property taxes are based on a fraction of the assessed value of the solar system. The method of assessment, and the tax rate, vary from state to state and sometimes from county to county within the state. The office of the county treasurer can provide detailed information on method of assessed valuation and the tax rate. Usually, the assessed value is a market value of the property, and the tax rate is applied to a fraction of the assessed value. The property tax rate varies widely, from zero in some states to ten percent in others. The property tax can be calculated as:

$$\text{Property Tax} = (\text{System cost}) \times (\text{Fraction for taxable value}) \times (\text{tax rate})$$

Insurance rates on houses with a solar system, at present, are the same as for houses without solar systems. The basic insurance rate depends upon the type of house construction and location of the building within or outside a city or town. The insurance rate for a comprehensive homeowners policy differs from that for a straight fire insurance policy,and the insurance rates for earthquake and flood damage (which are federally subsidized) are the only special insurances available for owners of buildings. The information on various insurance rates is available from local insurance agents. However, very few insurance companies have established insurance rates for solar systems. Damage to the contents of a building resulting from leaks in piping or storage tanks or damage to the solar system resulting from flooding by natural causes is based on comprehensive or flood insurance rates. Although there are many factors to be considered, the annual premium on insurance for houses with solar systems is less than one percent of the value of the house and contents, and ranges from 0.3 to about 0.6 percent.

The "savings" on state and federal income taxes for interest paid on the mortgage can be substantial, depending upon the "tax bracket" of the homeowner. The amount of interest paid annually on the mortgage decreases with the number of years remaining on the mortgage. The portion of annual mortgage which is paid as interest can be determined from the graphs on Figure 15-5. The use of curves in the figure is illustrated in the following example.

Let us assume that a loan of $10,000 has been secured at a term of 20 years and 9 percent interest. The annual mortgage payment was computed in the previous section to be $1100. Of that mortgage payment, $900 is for payment of interest in the first year, which amounts to 82 percent of

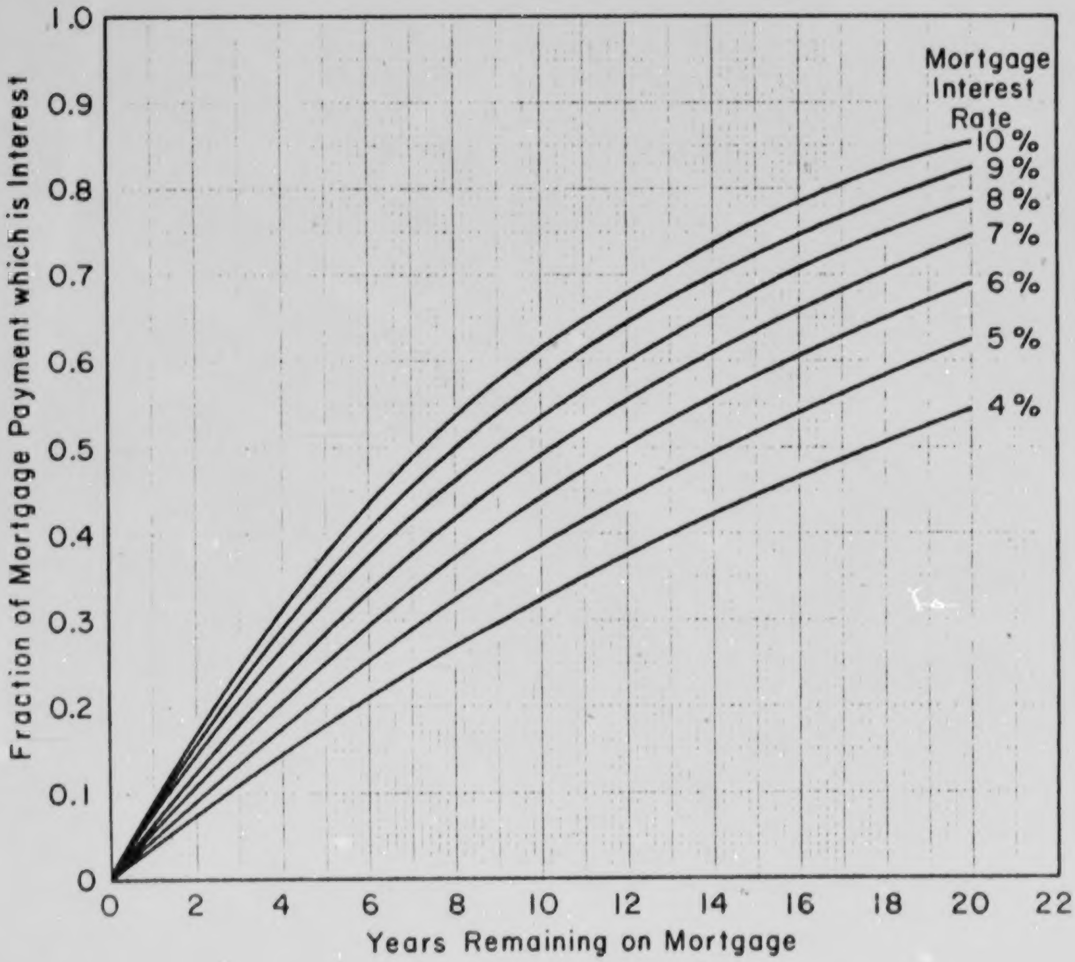

Figure 15-5. Fraction of Mortgage Payment Which is Interest

the mortgage payment. As this is the first year of payment, 20 years remain on the mortgage at the beginning of the year. By following the vertical line corresponding to 20 years in Figure 15-5, to the 9 percent curve, it is seen that the fraction of mortgage payment, which is interest, during the first year is 0.82. In the eleventh year, with ten years remaining on the mortgage at the beginning of the year, the interest paid during the year is (0.575) x ($1100), or $632. The income tax savings on a federal or state return would be:

$$\begin{pmatrix}\text{Income}\\ \text{tax credit}\end{pmatrix} = \begin{pmatrix}\text{Interest paid}\\ \text{on loan}\end{pmatrix} \times \begin{pmatrix}\text{Tax rate based}\\ \text{on net income}\end{pmatrix}$$

The federal income tax return provides credit for state income taxes paid and many states give credit for federal income taxes. Thus the full credit for tax savings resulting from payment of interest is not simply the sum of state and federal tax savings. The net effective rate is:

$$\begin{pmatrix}\text{Net}\\ \text{Effective}\\ \text{Rate}\end{pmatrix} = \begin{pmatrix}\text{Federal}\\ \text{tax rate}\end{pmatrix} + \begin{pmatrix}\text{State}\\ \text{tax rate}\end{pmatrix} - 2\begin{pmatrix}\text{Federal}\\ \text{tax rate}\end{pmatrix} \times \begin{pmatrix}\text{State}\\ \text{tax rate}\end{pmatrix}$$

If the income tax rate on a federal tax return is 25 percent and on a state tax return is 10 percent, the net effective rate is (0.25 + 0.10 - 2 x 0.25 x 0.10 =) 0.30, or 30 percent. Thus net annual income tax savings realized on the federal and state taxes for the first year, in the previous example, are (0.30) x $900), or $270 and, in the eleventh year, (0.30) x ($632), or $190.

OPERATING COSTS

The cost of operating a solar heating system, including the cost for operating the auxiliary unit in the system, is the cost of electric energy required to operate the pumps, central heat distribution fan, valves, and controller in a hydronic system, and the blowers, motorized dampers, and controller in an air system. The amount of energy used to collect, store, and distribute solar energy varies from system to system in the range from 5 to 10 percent of the total solar energy collected. The lower values in the range apply to low-head systems with small pressure drops, and air systems with single blowers with small pressure drops. The higher values in the range apply to high-head systems with large pressure drops, small systems with large pumps, and air systems with two blowers.

The operating cost for a non-solar system is much less than for a solar system. Although the blower size for distributing air to the rooms is the same, the power requirement is less for a non-solar system because the pressure drop in the system is lower. As an approximation, the energy required to operate a non-solar system is two percent of the total annual heating load.

MAINTENANCE COSTS

The maintenance costs for solar systems are unknown; there is insufficient long-term experience with various systems to indicate an appropriate annual maintenance cost. While there is one air system that has been operated continuously for 19 years, on which the maintenance cost was zero, it can be expected that all solar systems will require some amount of maintenance during the life of the systems. For the purpose of economic analysis, the maintenance cost for the first year can be estimated to be a nominal amount, say one hundred dollars, which will be escalated annually at a selected inflation rate.

LIFE CYCLE COST ANALYSIS

A life cycle cost analysis provides a means of determining the net savings realized with a solar system as compared to a non-solar system. Annual cash flows are calculated for the systems and the difference will determine the savings possible with a solar system over the non-solar system.

The method of life cycle cost analysis enables one to determine not only if a given solar system is economical, but the optimum economical size of the solar system. By analyzing several (at least three) different collector areas for the solar system, the size of the solar system which will yield the greatest savings over a comparable number of years will be the most economical. The methodology is outlined in the form of worksheets.

WORKSHEET LCA-1

Worksheet LCA-1 is used to calculate the installed cost of the solar system, the mortgage payment, tax rates and insurance, and the annual operating and maintenance costs. The first year expense of a non-solar system is also determined.

Worksheet LCA-1

LIFE CYCLE COST ANALYSIS
BASIC DATA

BUILDING DATA (see worksheet TA-1)
A. Building annual heat load (in million Btu) ______(m Btu)
B. Service hot water load (in million Btu) ______(m Btu)
C. Total annual load ______(m Btu)

SOLAR SYSTEM DATA (see worksheet TA-2)
D. Collector area ______(ft^2)
E. Fraction of annual load carried by solar ______(%/100)
F. Unit cost of solar system installed ______($/$ft^2$)
G. Installed cost of solar system (D x F) ______ x ______ ______($)
H. Type of auxiliary heaters:
H.1 Space ______________
H.2 Service hot water __________
I. Efficiencies of auxiliary heaters:
I.1 Space ______________(%/100)
I.2 Service hot water __________(%/100)
J. Auxiliary energy costs (see Figures 15-1, 15-2)
J.1 Space ______________($/m Btu)
J.2 Service hot water __________($/m Btu)

FINANCIAL DATA
K. Terms of loan: Years ______ Interest rate ______(%/100)
L. Down payment on loan: (______%/100 x G ______) ______($)
M. Amount of loan: G - L ______($)
N. Annual mortgage payment
Factor from Figure 15-4 ______ x M ______($/year)

TAXES AND INSURANCE
P. Property tax: G ______ x P.1 ______ x P.2 ______ ______($/year)
P.1 Ratio of taxable value to installed cost __________(%/100)
P.2 Property tax rate __________(%/100)
Q. Income tax rate:
Q.1 Federal tax rate __________(%/100)
Q.2 State tax rate __________(%/100)
Q.3 Effective tax rate[(Q.1 + Q.2 - 2(Q.1)(Q.2)] ______(%/100)
R. Insurance: [G ______ x Insurance rate ______ (%/100)] ______($/year)

OPERATION AND MAINTENANCE
S. Operating cost first year:
(S.1 x S.2 x J.1) ______ m Btu x ______
x ______ $/m Btu ______($/year)
S.1 Annual solar heat supplied (E x C)
______ x ______ = ______(m Btu)
S.2 Fraction of solar for electricity ______ (%/100)
T. Maintenance cost first year ______($/year)

NON SOLAR SYSTEM DATA
U. Fuel expenses in first year:
U.1 Space (A ______ x J.1 ______) ______($/year)
U.2 Service hot water: (B ______ x J.2 ______) ______($/year)
U.3 Total load (U.1 + U.2) ______($/year)
V. Operating expenses in first year (U.3 x 0.03) ______($/year)
W. Fuel plus operating expenses in first year (U.3 + V) ______($/year)

WORKSHEET LCA-2

The annual cash flows for a solar system for one collector area are determined from worksheet LCA-2.

The collector area is an arbitrary value and the solar fraction of total load is determined by using worksheet TA-2. The auxiliary fuel inflation rate is estimated and, if desired, a different general inflation rate can be specified.

Column [1] is the year into the future for which the analysis may be made. A reasonable economic analysis can be made for 15 to 20 years into the future.

Column [2] is the annual mortgage payment determined from LCA-1, line N. If the mortgage payment is a fixed annual amount, the payment for all future years would be the same as the first year.

Column [3] is the years remaining on the mortgage at the beginning of the year. At the beginning of the first year of a 20-year mortgage, there would be 20 years remaining.

Column [4] is the fraction of the mortgage payment which is paid as interest. The fraction decreases with increasing years and may be determined from Figure 15-5 for the particular interest rate of the mortgage.

Column [5] is the portion of the mortgage which is paid as interest, and is the product of column [2] times column [4].

Column [6] is auxiliary fuel cost. Because of expected fuel cost increases, the first year fuel cost will increase for subsequent years. The first year fuel cost is determined from worksheet LCA-1 as follows:

Worksheet LCA-2

LIFE CYCLE COST ANALYSIS
CASH FLOW

A. Mortgage interest rate ________ %/100
B. Auxiliary fuel inflation rate ________ %/100
C. General inflation rate ________ %/100

Collector area ________________ ft^2
Solar fraction of total load ______ %/100
(use worksheet TA-2)

System Cost $________
Down Payment $________

[1] Year	[2] Annual Mortgage Payment	[3] Years Left on Mortgage	[4] Frac. of Mortgage as Interest	[5] Interest Paid	[6] Auxiliary Fuel Cost	[7] Property Tax	[8] Insurance	[9] Operating Cost	[10] Maintenance Cost	[11] Income Tax Savings	[12] Expense with Solar
1											
2											
3											
4											
5											
6											
7											
8											
9											
10											
11											
12											
13											
14											
15											
16											
17											
18											
19											
20											

[2] Annual mortgage payment from LCA-1, line N
[4] See Figure 15-5
[5] Column [2] x column [4]
[6] First year cost from worksheet LCA-1:
(C) x (1 - E) X (J.1)
Second and future years:
(previous year cost) x (1 + fuel inflation rate)
[7] See line P, worksheet LCA-1
[8] See line R, worksheet LCA-1
[9] First year cost see line S, worksheet LCA-1
Second and future years:
(previous year cost) x (1 + fuel inflation rate)
[10] First year cost see line T, worksheet LCA-1
Second and future years:
(previous year cost) x (1 + general inflation rate)
[11] Column [5] x (Q.3, worksheet LCA-1)
[12] Downpayment + [2]+[6]+[7]+[8]+[9]+[10]-[11]

$$\begin{bmatrix}\text{First year}\\ \text{auxiliary}\\ \text{fuel cost}\end{bmatrix} = \begin{bmatrix}\text{Building}\\ \text{Annual}\\ \text{Total Load}\\ \text{C}\end{bmatrix} \times \begin{bmatrix}\text{Fraction of}\\ \text{Annual Load}\\ \text{Carried by}\\ \text{Auxiliary 1-E}\end{bmatrix} \times \begin{bmatrix}\text{Auxiliary}\\ \text{Energy}\\ \text{Cost}\\ \text{J.1}\end{bmatrix}$$

The second year fuel cost is determined by multiplying the first year cost by (1 + fuel inflation rate). For example, if the first year fuel cost is $400 and the fuel inflation rate is 7 percent, the second year cost is (400 x 1.07 =) $428. The fuel cost for each succeeding year is determined by multiplying the previous year by (1 + fuel inflation rate). The inflation rate may be changed for any year.

Column [7] is the annual property tax determined on line P on Worksheet LCA-1.

Column [8] is the annual insurance premium determined on line R on Worksheet LCA-1.

Column [9] is the annual operating cost of the solar system. The operating cost for the first year is determined on line S of Worksheet LCA-1. The cost for each succeeding year is determined by multiplying the previous year cost by (1 + electricity inflation rate). The cost for electricity is expected to increase at the fuel inflation rate.

Column [10] is the annual maintenance cost. The first year cost is estimated on line T of Worksheet LCA-1. The annual increase in maintenance cost can be estimated arbitrarily, or the cost can be estimated by multiplying the first year cost by (1 + general inflation rate).

Column [11] is the income tax savings calculated by the product of the effective tax rate on line Q.3 of Worksheet LCA-1, and the annual interest paid, in column [5].

Column [12] is the annual expense of a solar system and is determined by: column [2] + column [6] + column [7] + column [8] + column [9] + column [10] - column [11] = column [12].

WORKSHEET LCA-3

Worksheet LCA-3 is used to calculate the solar savings for solar systems with three different collector areas.

Column [1] is the year into the future for which the analysis may be made and should correspond with worksheet LCA-2.

Column [2] is the total fuel and operating cost for the non-solar system. The first year cost is the amount on line W of worksheet LCA-1. The costs in succeeding years are determined by multiplying the cost for the previous year by (1 + fuel inflation rate).

Column [3] is the expense with a solar system and is obtained from column [12] of worksheet LCA-2 for a given collector area.

Column [4] is the savings expected with a solar system and is the amount in column [2] minus the amount in column [3].

Column [5] is the cumulative saving with a solar system and is the running sum of column [4].

Columns [6] and [9] are the expenses with a solar system for different size collectors, obtained from worksheet LCA-2.

Columns [7] and [10] are the savings expected with different collector sizes, determined from (the cost of the non-solar system) - (cost with a solar system).

Columns [8] and [11] are the cumulative savings expected with the collector sizes specified. The collector area yielding the greatest savings is the size that is more economical to install.

LIFE CYCLE COST ANALYSIS
ECONOMIC SUMMARY

A. Fuel inflation rate ________(%/100)

[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]
Year	NON-SOLAR SYSTEM	SOLAR SYSTEM								
		Collector area _____ ft^2			Collector area _____ ft^2			Collector Area _____ ft^2		
	Fuel Plus Operating Expense	Expense with Solar from LCA-2	Savings with Solar [2] - [3]	Cumul. Savings with Solar	Expense with Solar from LCA-2	Savings with Solar [2] - [3]	Cumul. Savings with Solar	Expense with Solar from LCA-2	Savings with Solar [2] - [3]	Cumul. Savings with Solar
1										
2										
3										
4										
5										
6										
7										
8										
9										
10										
11										
12										
13										
14										
15										
16										
17										
18										
19										
20										

[2] First year cost, see line W of worksheet LCA-1
Second and future year:
(previous year cost) x (1 + fuel inflation rate)
[3] Column [12], worksheet LCA-2
[4] Column [2] - column [3]

[6] Column [12], worksheet LCA-2
[7] Column [2] - column [6]
[9] Column [12], worksheet LCA-2
[10] Column [2] - column [9]

EXAMPLE

A building in Podunk, U.S.A., has an annual space heating load of 100 m Btu and water heating load of 15 m Btu. A solar system for the building having 400 ft^2 of collector is calculated to provide 50 percent of the annual heating load. Electricity at 3¢/kWh is available and electric auxiliary heating is the only basis on which a loan can be secured.

The terms of the loan are 20 years at 9 percent with 20 percent downpayment. Property tax amounts to 2 percent on one-half the market value of the system, insurance is 0.5 percent of installed cost and the owner's income tax bracket is 30 percent for federal and 10 percent for the state income tax return. The electricity to operate the solar system is 5 percent of the total solar energy delivered as useful heat, and maintenance cost is $100 for the first year.

Electricity cost is estimated to escalate at 7 percent per year and general inflation rate will probably remain at 6 percent for the forseeable future. Determine the annual cash flow for the owner of the solar system for the next 20 years.

Worksheet LCA-1

LIFE CYCLE COST ANALYSIS
BASIC DATA

BUILDING DATA (see worksheet TA-1)

A. Building annual heat load (in million Btu) 100 (m Btu)
B. Service hot water load (in million Btu) 15 (m Btu)
C. Total annual load 115 (m Btu)

SOLAR SYSTEM DATA (see worksheet TA-2)

D. Collector area 400 (ft^2)
E. Fraction of annual load carried by solar 0.50 (%/100)
F. Unit cost of solar system installed 20 ($/ft2)
G. Installed cost of solar system (D x F) 400 x 20 8000 ($)
H. Type of auxiliary heaters:
H.1 Space Electric
H.2 Service hot water Electric
I. Efficiencies of auxiliary heaters:
I.1 Space 1.00 (%/100)
I.2 Service hot water 1.00 (%/100)
J. Auxiliary energy costs (see Figures 15-1, 15-2)
J.1 Space 8.80 ($/m Btu)
J.2 Service hot water 8.80 ($/m Btu)

FINANCIAL DATA

K. Terms of loan: Years 20 Interest rate 0.09 (%/100)
L. Down payment on loan: (20 %/100 x G 8000) 1600 ($)
M. Amount of loan: G - L 6400 ($)
N. Annual mortgage payment
Factor from Figure 15-4 0.11 x M 704 ($/year)

TAXES AND INSURANCE

P. Property tax: G 8000 x P.1 0.5 x P.2 0.02 80 ($/year)
P.1 Ratio of taxable value to installed cost 0.5 (%/100)
P.2 Property tax rate 0.02 (%/100)
Q. Income tax rate:
Q.1 Federal tax rate 0.30 (%/100)
Q.2 State tax rate 0.10 (%/100)
Q.3 Effective tax rate [(Q.1 + Q.2 - 2(Q.1)(Q.2)] 0.36 (%/100)
R. Insurance: [G 8000 x Insurance rate .005 (%/100)] 40 ($/year)

OPERATION AND MAINTENANCE

S. Operating cost first year:
(S.1 x S.2 x J.1) 57.5 m Btu x .05
x 8.80 $/m Btu 25 ($/year)
S.1 Annual solar heat supplied (E x C)
0.50 x 115 = 57.5 (m Btu)
S.2 Fraction of solar for electricity 0.05 (%/100)
T. Maintenance cost first year 100 ($/year)

NON SOLAR SYSTEM DATA

U. Fuel expenses in first year:
U.1 Space (A 100 x J.1 8.80) 880 ($/year)
U.2 Service hot water: (B 15 x J.2 8.80) 132 ($/year)
U.3 Total load (U.1 + U.2) 1012 ($/year)
V. Operating expenses in first year (U.3 x 0.03) 30 ($/year)
W. Fuel plus operating expenses in first year (U.3 + V) 1042 ($/year)

LIFE CYCLE COST ANALYSIS
CASH FLOW

A. Mortgage interest rate .09 %/100
B. Auxiliary fuel inflation rate .07 %/100
C. General inflation rate .06 %/100

Collector area 400 ft^2
Solar fraction of total load .5 %/100
(use worksheet TA-2)

System Cost $ 8,000
Down Payment $ 1,600

[1] Year	[2] Annual Mortgage Payment	[3] Years Left on Mortgage	[4] Frac. of Mortgage as Interest	[5] Interest Paid	[6] Auxiliary Fuel Cost	[7] Property Tax	[8] Insurance	[9] Operating Cost	[10] Maintenance Cost	[11] Income Tax Savings	[12] Expense with Solar
1	704	20	0.820	577	440	80	40	22	100	208	2778
2	704	19	0.805	567	471	80	40	24	106	204	1221
3	704	18	0.785	553	504	80	40	25	112	199	1266
4	704	17	0.765	539	539	80	40	27	119	194	1315
5	704	16	0.745	525	577	80	40	29	126	189	1367
6	704	15	0.720	507	617	80	40	31	134	183	1423
7	704	14	0.700	493	660	80	40	33	142	177	1482
8	704	13	0.670	472	707	80	40	35	150	170	1546
9	704	12	0.640	451	756	80	40	38	159	162	1615
10	704	11	0.610	429	809	80	40	40	169	154	1688
11	704	10	0.575	405	866	80	40	43	179	146	1766
12	704	9	0.540	380	926	80	40	46	190	137	1849
13	704	8	0.500	352	991	80	40	50	201	127	1939
14	704	7	0.450	317	1060	80	40	53	213	114	2036
15	704	6	0.400	282	1135	80	40	57	226	102	2140
16	704	5	0.350	246	1214	80	40	61	240	89	2250
17	704	4	0.290	204	1298	80	40	65	254	73	2368
18	704	3	0.230	162	1390	80	40	69	269	58	2494
19	704	2	0.160	113	1487	80	40	74	285	41	2629
20	704	1	0.085	60	1593	80	40	80	303	22	2778

[2] Annual mortgage payment from LCA-1, line N
[4] See Figure 15-5
[5] Column [2] x column [4]
[6] First year cost from worksheet LCA-1:
(C) x (1 - E) X (J.1)
Second and future years:
(first year cost) x (1 + fuel inflation rate)
[7] See line P, worksheet LCA-1
[8] See line R, worksheet LCA-1
[9] First year cost see line S, worksheet LCA-1
Second and future years:
(previous year cost) x (1 + fuel inflation rate)
[10] First year cost see line T, worksheet LCA-1
Second and future years:
(previous year cost) x (1 + general inflation rate)
[11] Column [5] x (Q.3, worksheet LCA-1)
[12] Downpayment + [2]+[6]+[7]+[8]+[9]+[10]-[11]

BLANK WORKSHEET FORMS

Worksheet LCA-1

LIFE CYCLE COST ANALYSIS
BASIC DATA

BUILDING DATA (see worksheet TA-1)

A. Building annual heat load (in million Btu) ______(m Btu)
B. Service hot water load (in million Btu) ______(m Btu)
C. Total annual load ______(m Btu)

SOLAR SYSTEM DATA (see worksheet TA-2)

D. Collector area ______(ft^2)
E. Fraction of annual load carried by solar ______(%/100)
F. Unit cost of solar system installed ______($\$/ft^2$)
G. Installed cost of solar system (D x F) ______x______ ______($)
H. Type of auxiliary heaters:
  H.1 Space ____________________
  H.2 Service hot water __________
I. Efficiencies of auxiliary heaters:
  I.1 Space ____________________(%/100)
  I.2 Service hot water __________(%/100)
J. Auxiliary energy costs (see Figures 15-1, 15-2)
  J.1 Space ____________________($/m Btu)
  J.2 Service hot water __________($/m Btu)

FINANCIAL DATA

K. Terms of loan: Years _____ Interest rate ______(%/100)
L. Down payment on loan: (______%/100 x G ______) ______($)
M. Amount of loan: G - L ______($)
N. Annual mortgage payment
  Factor from Figure 15-4 ______ x M ______($/year)

TAXES AND INSURANCE

P. Property tax: G ______ x P.1 ______ x P.2 ______ ______($/year)
  P.1 Ratio of taxable value to installed cost ____________(%/100)
  P.2 Property tax rate __________(%/100)
Q. Income tax rate:
  Q.1 Federal tax rate __________(%/100)
  Q.2 State tax rate __________(%/100)
  Q.3 Effective tax rate[(Q.1 + Q.2 - 2(Q.1)(Q.2)] ______(%/100)
R. Insurance: [G ______ x Insurance rate ______(%/100)] ______($/year)

OPERATION AND MAINTENANCE

S. Operating cost first year:
  (S.1 x S.2 x J.1) ________ m Btu x ________
  x ______ $/m Btu ______($/year)
  S.1 Annual solar heat supplied (E x C)
  ______ x ______ = ______(m Btu)
  S.2 Fraction of solar for electricity ______ (%/100)
T. Maintenance cost first year ______($/year)

NON SOLAR SYSTEM DATA

U. Fuel expenses in first year:
  U.1 Space (A ______ x J.1 ______) ______($/year)
  U.2 Service hot water: (B ______ x J.2 ______) ______($/year)
  U.3 Total load (U.1 + U.2) ______($/year)
V. Operating expenses in first year (U.3 x 0.03) ______($/year)
W. Fuel plus operating expenses in first year (U.3 + V) ______($/year)

LIFE CYCLE COST ANALYSIS
BASIC DATA

BUILDING DATA (see worksheet TA-1)

A. Building annual heat load (in million Btu) ______(m Btu)
B. Service hot water load (in million Btu) ______(m Btu)
C. Total annual load ______(m Btu)

SOLAR SYSTEM DATA (see worksheet TA-2)

D. Collector area ______(ft^2)
E. Fraction of annual load carried by solar ______(%/100)
F. Unit cost of solar system installed ______($/ft2)
G. Installed cost of solar system (D x F) ______ x ______ ______($)
H. Type of auxiliary heaters:
  H.1 Space ____________________
  H.2 Service hot water__________
I. Efficiencies of auxiliary heaters:
  I.1 Space____________________(%/100)
  I.2 Service hot water__________(%/100)
J. Auxiliary energy costs (see Figures 15-1, 15-2)
  J.1 Space____________________($/m Btu)
  J.2 Service hot water__________($/m Btu)

FINANCIAL DATA

K. Terms of loan: Years______ Interest rate______(%/100)
L. Down payment on loan: (______%/100 x G ______) ______($)
M. Amount of loan: G - L ______($)
N. Annual mortgage payment
  Factor from Figure 15-4 ______ x M ______($/year)

TAXES AND INSURANCE

P. Property tax: G______ x P.1 ______ x P.2 ______ ______($/year)
  P.1 Ratio of taxable value to installed cost __________(%/100)
  P.2 Property tax rate__________(%/100)
Q. Income tax rate:
  Q.1 Federal tax rate__________(%/100)
  Q.2 State tax rate __________(%/100)
  Q.3 Effective tax rate[(Q.1 + Q.2 - 2(Q.1)(Q.2)] ______(%/100)
R. Insurance: [G ______ x Insurance rate ______ (%/100)] ______($/year)

OPERATION AND MAINTENANCE

S. Operating cost first year:
  (S.1 x S.2 x J.1) ________ m Btu x ______
  x ______ $/m Btu ______($/year)
  S.1 Annual solar heat supplied (E x C)
  ______ x ______ = ______(m Btu)
  S.2 Fraction of solar for electricity ______ (%/100)
T. Maintenance cost first year ______($/year)

NON SOLAR SYSTEM DATA

U. Fuel expenses in first year:
  U.1 Space (A ______ x J.1 ________) ______ ($/year)
  U.2 Service hot water: (B ______ x J.2 ________) ______ ($/year)
  U.3 Total load (U.1 + U.2) ______ ($/year)
V. Operating expenses in first year (U.3 x 0.03) ______ ($/year)
W. Fuel plus operating expenses in first year (U.3 + V) ______ ($/year)

Worksheet LCA-2

LIFE CYCLE COST ANALYSIS
CASH FLOW

A. Mortgage interest rate ________%/100
B. Auxiliary fuel inflation rate ________%/100
C. General inflation rate ________%/100

Collector area ________________ft^2
Solar fraction of total load ______%/100
(use worksheet TA-2)

System Cost $ __________
Down Payment $ __________

[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]	[12]
Year	Annual Mortgage Payment	Years Left on Mortgage	Frac. of Mortgage as Interest	Interest Paid	Auxiliary Fuel Cost	Property Tax	Insurance	Operating Cost	Maintenance Cost	Income Tax Savings	Expense with Solar
1											
2											
3											
4											
5											
6											
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11											
12											
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17											
18											
19											
20											

[2] Annual mortgage payment from LCA-1, line N
[4] See Figure 15-5
[5] Column [2] x column [4]
[6] First year cost from worksheet LCA-1:
(C) x (1 - E) X (J.1)
Second and future years:
(first year cost) x (1 + fuel inflation rate)
[7] See line P, worksheet LCA-1
[8] See line R, worksheet LCA-1
[9] First year cost see line S, worksheet LCA-1
Second and future years:
(previous year cost) x (1 + fuel inflation rate)
[10] First year cost see line T, worksheet LCA-1
Second and future years:
(previous year cost) x (1 + general inflation rate)
[11] Column [5] x (Q.3, worksheet LCA-1)
[12] Downpayment + [2]+[6]+[7]+[8]+[9]+[10]-[11]

Worksheet LCA-2

LIFE CYCLE COST ANALYSIS
CASH FLOW

A. Mortgage interest rate ________%/100
B. Auxiliary fuel inflation rate ______%/100
C. General inflation rate ________%/100

Collector area ______________ ft^2
Solar fraction of total load ______%/100
(use worksheet TA-2)

System Cost $ __________
Down Payment $ __________

[1] Year	[2] Annual Mortgage Payment	[3] Years Left on Mortgage	[4] Frac. of Mortgage as Interest	[5] Interest Paid	[6] Auxiliary Fuel Cost	[7] Property Tax	[8] Insurance	[9] Operating Cost	[10] Maintenance Cost	[11] Income Tax Savings	[12] Expense with Solar
1											
2											
3											
4											
5											
6											
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11											
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16											
17											
18											
19											
20											

[2] Annual mortgage payment from LCA-1, line N
[4] See Figure 15-5
[5] Column [2] x column [4]
[6] First year cost from worksheet LCA-1:
(C) x (1 - E) X (J.1)
Second and future years:
(first year cost) x (1 + fuel inflation rate)
[7] See line P, worksheet LCA-1

[8] See line R, worksheet LCA-1
[9] First year cost see line S, worksheet LCA-1
Second and future years:
(previous year cost) x (1 + fuel inflation rate)
[10] First year cost see line T, worksheet LCA-1
Second and future years:
(previous year cost) x (1 + general inflation rate)
[11] Column [5] x (Q.3, worksheet LCA-1)
[12] Downpayment + [2]+[6]+[7]+[8]+[9]+[10]-[11]

LIFE CYCLE COST ANALYSIS
ECONOMIC SUMMARY

A. Fuel inflation rate _______(%/100)

[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]
Year	NON-SOLAR SYSTEM	SOLAR SYSTEM								
		Collector area _____ft^2			Collector area _____ft^2			Collector Area _____ft^2		
	Fuel Plus Operating Expense	Expense with Solar from LCA-2	Savings with Solar [2] - [3]	Cumul. Savings with Solar	Expense with Solar from LCA-2	Savings with Solar [2] - [3]	Cumul. Savings with Solar	Expense with Solar from LCA-2	Savings with Solar [2] - [3]	Cumul. Savings with Solar
1										
2										
3										
4										
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11										
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15										
16										
17										
18										
19										
20										

[2] First year cost, see line W of worksheet LCA-1
Second and future year:
(previous year cost) x (1 + fuel inflation rate)
[3] Column [12], worksheet LCA-2
[4] Column [2] - column [3]

[6] Column [12], worksheet LCA-2
[7] Column [2] - column [6]
[9] Column [12], worksheet LCA-2
[10] Column [2] - column [9]

Worksheet LCA-3

LIFE CYCLE COST ANALYSIS
ECONOMIC SUMMARY

A. Fuel inflation rate _______(%/100)

[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]
Year	NON-SOLAR SYSTEM	SOLAR SYSTEM								
		Collector area _____ ft^2			Collector area _____ ft^2			Collector Area _____ ft^2		
	Fuel Plus Operating Expense	Expense with Solar from LCA-2	Savings with Solar [2] - [3]	Cumul. Savings with Solar	Expense with Solar from LCA-2	Savings with Solar [2] - [3]	Cumul. Savings with Solar	Expense with Solar from LCA-2	Savings with Solar [2] - [3]	Cumul. Savings with Solar
1										
2										
3										
4										
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12										
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14										
15										
16										
17										
18										
19										
20										

[2] First year cost, see line W of worksheet LCA-1
Second and future year:
(previous year cost) x (1 + fuel inflation rate)
[3] Column [12], worksheet LCA-2
[4] Column [2] - column [3]

[6] Column [12], worksheet LCA-2
[7] Column [2] - column [6]
[9] Column [12], worksheet LCA-2
[10] Column [2] - column [9]

SOLAR SYSTEM DATA

Building Owner: ____________________

Address: ____________________

Contractor: ____________________

Type of Solar System (air or liquid) __________

A. Location: Nearest city ______________ Latitude (ℓ) ________

B. Mean daily solar radiation in January (s) __________ (Btu/ft^2·day)

C. January solar radiation on a horizontal surface (S)
(B x 31) = __________ (Btu/ft^2·month)

D. January building heat load (L) ______________ (Btu/month)

E. January solar radiation : January building load
(S ÷ L) = __________ (1/ft^2)

F. Collector tilt ________: ℓ + ______ or ℓ - ______

G. Collector Orientation ________ degrees, __________ from south

H. Heat Exchanger Temperature Difference (Liquid systems only) ______ °F

I. Fraction of annual heating load:

[1]	[2]	[3]	[4]	[5]	[6]	[7]
Trial Number	Trial Collector Area at Tilt = Latitude A	Area Corrected for Tilt A	Area Corrected for Orientation A	Area Corrected for Heat Exchanger A	$\frac{SA}{L}$	f

[2] Selected arbitrarily or determined from f

[3] Correction to column [2] for tilt not equal to latitude + 15° (Fig. 14-2)

[4] Correction to column [3] for orientation (Fig. 14-3)

[5] Correction to column [4] for heat exchanger (liquid systems only)

[6] From Figure 14-1

[7] Selected arbitrarily or determined from Figure 14-1

SOLAR SYSTEM DATA

Building Owner: ____________________

Address: ____________________

Contractor: ____________________

Type of Solar System (air or liquid) ____________

A. Location: Nearest city ____________ Latitude (ℓ) ________

B. Mean daily solar radiation in January (s) ____________ (Btu/ft^2·day)

C. January solar radiation on a horizontal surface (S)
(B x 31) = ____________ (Btu/ft^2·month)

D. January building heat load (L) ____________ (Btu/month)

E. January solar radiation : January building load
(S ÷ L) = ____________ (1/ft^2)

F. Collector tilt ________: ℓ + ________ or ℓ - ________

G. Collector Orientation ________ degrees, ____________ from south

H. Heat Exchanger Temperature Difference (Liquid systems only) ______ °F

I. Fraction of annual heating load:

[1] Trial Number	[2] Trial Collector Area at Tilt = Latitude A	[3] Area Corrected for Tilt A	[4] Area Corrected for Orientation A	[5] Area Corrected for Heat Exchanger A	[6] $\frac{SA}{L}$	[7] f

[2] Selected arbitrarily or determined from f

[3] Correction to column [2] for tilt not equal to latitude + 15° (Fig. 14-2

[4] Correction to column [3] for orientation (Fig. 14-3)

[5] Correction to column [4] for heat exchanger (liquid systems only)

[6] From Figure 14-1

[7] Selected arbitrarily or determined from Figure 14-1

WORKSHEET TA-3

SOLAR SYSTEM SIZE

A. Type of System ______________

B. Economical Collector Area ______________ ft^2

C. Collector Tilt ______________ degree:

D. Collector Fluid Flow Rate:

1. Air System (1.5 to 2 cfm/ft^2 collector) ______________ cfm
2. Liquid System (0.02 gpm/ft^2 collector) ______________ gpm

E. Pumps: Liquid System

1. Collector loop flow rate (D.2) ______________ gpm
   Head ______________ ft
2. Storage loop flow rate (1.5 x E.1) ______________ gpm
   Head ______________ ft
3. Service water preheater ______3______ gpm
   Head ______2-3______ ft
4. Heat distribution coil (depends upon heat delivery rate) ______________ gpm
   Head ______________ ft

F. Blowers: Air System

1. Collector loop (D.1) ______________ cfm
   Head ______1-1.5______ in w.g.
2. Distribution blower (provided with furnace) ______________ cfm
   Head ______________ in w.g.
3. One blower system (D.1) ______________ cfm
   Head ______1-1.5______ in w.g.

G. Storage:

1. Liquid system B x 2.0 $gallons/ft^2$ collector ______________ gal
2. Air system B x 1/2 ft^3/ft^2 collector ______________ ft^3
   - (a) Pebble size (1-in. screened concrete aggregate)
   - (b) Cross-section area (D.1 : 20) ______________ ft^2
   - (c) Rock depth (G.2 : G.2.b) ______________ ft

H. Heat Exchangers:

Consult heat exchanger manufacturer

WORKSHEET TA-3

SOLAR SYSTEM SIZE

A. Type of System ______________

B. Economical Collector Area ______________ ft^2

C. Collector Tilt ______________ degrees

D. Collector Fluid Flow Rate:

1. Air System (1.5 to 2 cfm/ft^2 collector) ______________ cfm
2. Liquid System (0.02 gpm/ft^2 collector) ______________ gpm

E. Pumps: Liquid System

1. Collector loop flow rate (D.2) ______________ gpm
   Head ______________ ft
2. Storage loop flow rate (1.5 x E.1) ______________ gpm
   Head ______________ ft
3. Service water preheater ______3______ gpm
   Head ______2-3______ ft
4. Heat distribution coil (depends upon heat delivery rate) ______________ gpm
   Head ______________ ft

F. Blowers: Air System

1. Collector loop (D.1) ______________ cfm
   Head ______1-1.5______ in w.g.
2. Distribution blower (provided with furnace) ______________ cfm
   Head ______________ in w.g.
3. One blower system (D.1) ______________ cfm
   Head ______1-1.5______ in w.g.

G. Storage:

1. Liquid system B x 2.0 gallons/ft^2 collector ______________ gal
2. Air system B x 1/2 ft^3/ft^2 collector ______________ ft^3
   - (a) Pebble size (1-in. screened concrete aggregate)
   - (b) Cross-section area (D.1 : 20) ______________ ft^2
   - (c) Rock depth (G.2 : G.2.b) ______________ ft

H. Heat Exchangers:

Consult heat exchanger manufacturer

TRAINING COURSE IN
THE PRACTICAL ASPECTS OF
SIZING, INSTALLATION, AND OPERATION OF SOLAR HEATING AND COOLING SYSTEMS
FOR
RESIDENTIAL BUILDINGS

MODULE 16

SOLAR SYSTEM SIZING CALCULATIONS BY TRAINEES

SOLAR ENERGY APPLICATIONS LABORATORY
COLORADO STATE UNIVERSITY
FORT COLLINS, COLORADO

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INTRODUCTION

To calculate the size of a solar system for a residential building we need to know the monthly average daily solar energy available for the location of the house, the heating load, and collector size. The balance of the system can be sized from the collector area and the economic details for the system may be calculated if desired.

Worksheets are provided to make the necessary calculations. The worksheets are:

TA-1	Building Heating Load Calculations (2 sheets)
TA-2	Solar System Data
LCA-1	Life Cycle Cost Analysis, Basic Data
LCA-2	Life Cycle Cost Analysis, Cash Flow
LCA-3	Life Cycle Cost Analysis, Economic Summary
TA-3	Solar System Size

The worksheets are explained in detail in the following modules:

TA-1	Module 13
TA-2	Module 14
LCA-1 to LCA-3	Module 15

All the worksheets are reprinted in this module.

OBJECTIVE

The trainee should be able to select the most economical solar collector area for the system.

16-2

SYSTEM SIZING PROBLEM

Design an air heating solar system for a 3-bedroom house in Boulder, Colorado. The house is to be wood frame construction with R-13 wall insulation and R-19 ceiling insulation. The dimensions of the house are 27 by 55 feet on the main floor with a full basement and unheated garage. The ceiling height on the main floor rooms is 8'-0" and in the basement, 7'-3". There are 130 ft^2 of window area on the main floor with storm windows and two 3'-0" by 6'-8", 2.2" thick solid wood doors with wood frame storm doors. The basement has 30 ft^2 of windows with storm windows. Assume the building will have 4 occupants.

The installed cost of the system will vary from \$27/ft^2 for a system with 400 ft^2 of collectors to \$24/ft^2 for a system with 800 ft^2 of collectors. Electricity is the auxiliary energy for space and water heating, and current cost is 3.1¢/kWh. Prospects are that energy cost will increase at 8% inflation rate while the general inflation rate could be 6%.

The best loan negotiable is 20 years at 9 percent, with a 10 percent down payment. Property tax is 62 mils on 30 percent of assessed value which is at market. Assume there is a state law which exempts solar heating and cooling systems from property tax.

The owner of the building is assumed to be in the 30% tax bracket, and in Colorado, the state income tax rate is 8 percent for persons in the 30% federal tax bracket. The insurance premium on solar systems is the same rate as a homeowners policy, and can be obtained at 0.3 percent per year based on insured value.

The solution is given at the end of the module, but participants are encouraged to size the system on their own and determine the economical collector area for the system.

Worksheet TA-1
Sheet 1 of 2

Building Heat Load Calculations

Job Module 16 Problem
Computed by
Location Boulder Colorado

Number of Occupants 4
Date January 13, 1977
Latitude 40° N

Indoor temperature, T_R, 68 °F
Design winter outdoor temperature, T_O, -2 °F
Design temperature difference 70 °F
Design degree-day, 65 - T_O, 67 °F

Building Dimensions:
Above Grade: Length 55 ft Width 27 ft Ceiling Height 8 ft
Below Grade: Length 55 ft Width 27 ft Depth 7.25 ft
Concrete Floor Slab: Exposed perimeter 0 ft

Exterior Wall Area: $8 \times (55 + 27) \times 2 = 1312\ ft^2$

Window Area: $130\ ft^2$

Door Area: $2 \times (3 \times 6.67)$ $40\ ft^2$

Net Exterior Wall Area: $1142\ ft^2$

Ceiling Area: $1485\ ft^2$

Floor Area: $1485\ ft^2$

Basement Wall Area: $7.25 (55 + 27) \times 2 - 30 = 1159\ ft^2$

Heating Degree-Days:* January 1132 °F-days (Denver)
Annual 6283 °F-days

* From Table 13-2

Worksheet TA-1
Sheet 2 of 2

		U Btu/(hr)(ft^2)(°F)	A	ΔT °F (T_R - T_o)	h = UA ΔT Btu/hr
Exterior Walls (net)		.07	1142	70	5600
Basement Walls	Above grade				
	Below grade	.06	1159	23 *	1600
Windows and Sliding Patio Doors	Single				
	Double				
	Triple				
	Storm	.56	160	70	6270
Exterior Slab Doors		.24	40	70	670
Floors	Over Crawlspace				
	Concrete Slab on Grade				
	Basement	.06	1485	23*	2050
Ceiling		.05	1485	70	5200
Subtotal (walls, windows, doors, floors, ceiling)					21390
Infiltration: (0.018) x 27x55x8 ft^3 x 70 °F					14,970
Duct = 10% of subtotal (if ducts not in insulation envelope)					3640
Design Heating Load: Btu/hr					40,000
Design Heating Load: Btu/DD Design Heating Load (Btu/hr) X (24 hr/Design TD)					14,330
January Heating Load: m Btu (Btu/DD) X (January DD)					16.2
Annual Heating Load: m Btu (Btu/DD) X (Annual DD)					90.0

* ΔT = T_R - 45°

DOMESTIC HOT WATER LOAD

Number of occupants X 16,680 Btu/day	66720
January Load (m Btu) (Btu/day) x 31 x 10^{-6}	2.07
Annual Load (m Btu) (January load x 12)	24.84

Worksheet TA-2

SOLAR SYSTEM DATA

Building Owner: Module 16
Address: Boulder Colorado
Contractor:
Type of Solar System (air or liquid) Air

A. Location: Nearest city Boulder, CO Latitude (ℓ) 40

B. Mean daily solar radiation in January (s) = 201 x 3.69 = 740 (Btu/ft^2·day)

C. January solar radiation on a horizontal surface (S)
(B x 31) = 22,940 (Btu/ft^2·month)

D. January building heat load (L) 16,200,000 (Btu/month)

E. January solar radiation : January building load
(S ÷ L) = .001416 (1/ft^2)

F. Collector tilt 55 : ℓ + 15 or ℓ -

G. Collector Orientation 0 degrees, from south

H. Heat Exchanger Temperature Difference (Liquid systems only) 0 °F

I. Fraction of annual heating load:

[1] Trial Number	[2] Trial Collector Area at Tilt = Latitude A	[3] Area Corrected for Tilt A	[4] Area Corrected for Orientation A	[5] Area Corrected for Heat Exchanger A	[6] $\frac{SA}{L}$	[7] f
1	400				0.57	0.68
2	500				0.71	0.78
3	600				0.85	0.85
4	700				0.99	0.9

[2] Selected arbitrarily or determined from f

[3] Correction to column [2] for tilt not equal to latitude (Fig. 14-2)

[4] Correction to column [3] for orientation (Fig. 14-3)

[5] Correction to column [4] for heat exchanger (liquid systems only)

[6] From Figure 14-1

[7] Selected arbitrarily or determined from Figure 14-1

Worksheet LCA-1

LIFE CYCLE COST ANALYSIS
BASIC DATA

BUILDING DATA (see worksheet TA-1)

A. Building annual heat load (in million Btu) 90 (m Btu)
B. Service hot water load (in million Btu) 24.8 (m Btu)
C. Total annual load 114.8 (m Btu)

SOLAR SYSTEM DATA (see worksheet TA-2)

D. Collector area 400 (ft^2)
E. Fraction of annual load carried by solar .68 (%/100)
F. Unit cost of solar system installed 27 ($/ft2)
G. Installed cost of solar system (D x F) 400 x 27 10,800 ($)
H. Type of auxiliary heaters:
  H.1 Space electric resistance
  H.2 Service hot water Electric
I. Efficiencies of auxiliary heaters:
  I.1 Space 1.00 (%/100)
  I.2 Service hot water 1.00 (%/100)
J. Auxiliary energy costs (see Figures 15-1, 15-2)
  J.1 Space 9.00 ($/m Btu)
  J.2 Service hot water 9.00 ($/m Btu)

FINANCIAL DATA

K. Terms of loan: Years 20 Interest rate 9 (%/100)
L. Down payment on loan: (10 %/100 x G 10800) 1080 ($)
M. Amount of loan: G - L 9720 ($)
N. Annual mortgage payment
  Factor from Figure 15-4 0.11 x M 1069 ($/year)

TAXES AND INSURANCE

P. Property tax: G 10800 x P.1 .30 x P.2 .062 201 ($/year)
  P.1 Ratio of taxable value to installed cost 0.45 (%/100) (EXEMPT)
  P.2 Property tax rate .062 (%/100)
Q. Income tax rate:
  Q.1 Federal tax rate .30 (%/100)
  Q.2 State tax rate .08 (%/100)
  Q.3 Effective tax rate[(Q.1 + Q.2 - 2(Q.1)(Q.2)] 0.33 (%/100)
R. Insurance: [G 10,800 x Insurance rate .003 (%/100)] 32 ($/year)

OPERATION AND MAINTENANCE

S. Operating cost first year:
  (S.1 x S.2 x J.1) 78.1 m Btu x .06
  x 9.00 $/m Btu 42 ($/year)
  S.1 Annual solar heat supplied (E x C)
  0.68 x 114.8 = 78.1 (m Btu)
  S.2 Fraction of solar for electricity .06 (%/100)
T. Maintenance cost first year 50 ($/year)

NON SOLAR SYSTEM DATA

U. Fuel expenses in first year:
  U.1 Space (A 90 x J.1 9.00) 810 ($/year)
  U.2 Service hot water: (B 24.8 x J.2 9.00) 223 ($/year)
  U.3 Total load (U.1 + J.2) 1033 ($/year)
V. Operating expenses in first year (U.3 x 0.03) 31 ($/year)
W. Fuel plus operating expenses in first year (U.3 + V) 1064 ($/year)

LIFE CYCLE COST ANALYSIS
CASH FLOW

A. Mortgage interest rate .09 %/100
B. Auxiliary fuel inflation rate .08 %/100
C. General inflation rate .06 %/100

Collector area 400 ft^2
Solar fraction of total load .68 %/100
(use worksheet TA-2)

System Cost $ 10,800
Down Payment $ 1080

[1] Year	[2] Annual Mortgage Payment	[3] Years Left on Mortgage	[4] Frac. of Mortgage as Interest	[5] Interest Paid	[6] Auxiliary Fuel Cost	[7] Property Tax	[8] Insurance	[9] Operating Cost	[10] Maintenance Cost	[11] Income Tax Savings	[12] Expense with Solar
1	1069	20	.82	877	330	0	32	42	50	289	2314
2	1069	19	.805	861	357	0	32	45	53	284	1272
3	1069	18	.785	839	386	0	32	49	56	277	1315
4	1069	17	.765	818	416	0	32	53	60	270	1360
5	1069	16	.745	796	450	0	32	57	63	263	1408
6	1069	15	.720	770	486	0	32	62	67	254	1462
7	1069	14	.700	748	525	0	32	67	71	247	1517
8	1069	13	.670	716	567	0	32	72	75	236	1579
9	1069	12	.640	684	612	0	32	78	80	226	1645
10	1069	11	.610	652	661	0	32	84	84	215	1715
11	1069	10	.575	615	714	0	32	91	90	203	1793
12	1069	9	.540	577	771	0	32	98	95	190	1875
13	1069	8	.500	535	833	0	32	106	101	177	1964
14	1069	7	.450	481	899	0	32	114	107	159	2062
15	1069	6	.400	428	971	0	32	123	113	141	2167
16	1069	5	.350	374	1049	0	32	133	120	123	2280
17	1069	4	.290	310	1133	0	32	144	127	102	2403
18	1069	3	.230	246	1223	0	32	155	135	81	2533
19	1069	2	.160	171	1321	0	32	168	143	56	2677
20	1069	1	.085	91	1427	0	32	181	151	30	2830

[2] Annual mortgage payment from LCA-1, line N
[4] See Figure 15-5
[5] Column [2] x column [4]
[6] First year cost from worksheet LCA-1:
(C) x (1 - E) x (J.1)
Second and future years:
(first year cost) x (1 + fuel inflation rate)
[7] See line P, worksheet LCA-1

[8] See line R, worksheet LCA-1
[9] First year cost see line S, worksheet LCA-1
Second and future years:
(previous year cost) x (1 + fuel inflation rate)
[10] First year cost see line T, worksheet LCA-1
Second and future years:
(previous year cost) x (1 + general inflation rate)
[11] Column [5] x (Q.3, worksheet LCA-1)
[12] Downpayment + [2]+[6]+[7]+[8]+[9]+[10]-[11]

LIFE CYCLE COST ANALYSIS
BASIC DATA

BUILDING DATA (see worksheet TA-1)

A. Building annual heat load (in million Btu) 90 (m Btu)
B. Service hot water load (in million Btu) 24.8 (m Btu)
C. Total annual load 114.8 (m Btu)

SOLAR SYSTEM DATA (see worksheet TA-2)

D. Collector area 500 (ft²)
E. Fraction of annual load carried by solar .78 (%/100)
F. Unit cost of solar system installed 26 ($/ft2)
G. Installed cost of solar system (D x F) 500 x 26 13000 ($)
H. Type of auxiliary heaters:
    H.1 Space ________
    H.2 Service hot water ________
I. Efficiencies of auxiliary heaters:
    I.1 Space ________ (%/100)
    I.2 Service hot water ________ (%/100)
J. Auxiliary energy costs (see Figures 15-1, 15-2)
    J.1 Space 9.00 ($/m Btu)
    J.2 Service hot water 9.00 ($/m Btu)

FINANCIAL DATA

K. Terms of loan: Years 20 Interest rate 9 (%/100)
L. Down payment on loan: (10 %/100 x G 13000) 1300 ($)
M. Amount of loan: G - L 11,700 ($)
N. Annual mortgage payment
    Factor from Figure 15-4 .11 x M 1287 ($/year)

TAXES AND INSURANCE

P. Property tax: G 13000 x P.1 .30 x P.2 .062 242 ($/year)
    P.1 Ratio of taxable value to installed cost .45 (%/100)
    P.2 Property tax rate .062 (%/100)
Q. Income tax rate:
    Q.1 Federal tax rate .30 (%/100)
    Q.2 State tax rate .08 (%/100)
    Q.3 Effective tax rate[(Q.1 + Q.2 - 2(Q.1)(Q.2)] .33 (%/100)
R. Insurance: [G 13000 x Insurance rate .003 (%/100)] 39 ($/year)

OPERATION AND MAINTENANCE

S. Operating cost first year:
    (S.1 x S.2 x J.1) 89.5 m Btu x .06 x 9.00 $/m Btu 48 ($/year)
    S.1 Annual solar heat supplied (E x C)
        .78 x 114.8 = 89.5 (m Btu)
    S.2 Fraction of solar for electricity .06 (%/100)
T. Maintenance cost first year 50 ($/year)

NON SOLAR SYSTEM DATA

U. Fuel expenses in first year:
    U.1 Space (A ____ x J.1 ____) ____ ($/year)
    U.2 Service hot water: (B ____ x J.2 ____) ____ ($/year)
    U.3 Total load (U.1 + U.2) ____ ($/year)
V. Operating expenses in first year (U.3 x 0.03) ____ ($/year)
W. Fuel plus operating expenses in first year (U.3 + V) 1064 ($/year)

LIFE CYCLE COST ANALYSIS
CASH FLOW

A. Mortgage interest rate .09 %/100
B. Auxiliary fuel inflation rate .08 %/100
C. General inflation rate .06 %/100

Collector area 500 ft^2
Solar fraction of total load .78 %/100
(use worksheet TA-2)

System Cost $ 13,000
Down Payment $ 1300

[1] Year	[2] Annual Mortgage Payment	[3] Years Left on Mortgage	[4] Frac. of Mortgage as Interest	[5] Interest Paid	[6] Auxiliary Fuel Cost	[7] Property Tax	[8] Insurance	[9] Operating Cost	[10] Maintenance Cost	[11] Income Tax Savings	[12] Expense with Solar
1	1287	20	.820	1055	227	0	39	48	50	348	1603
2	1287	19	.805	1036	245	0	39	52	53	342	1334
3	1287	18	.785	1010	265	0	39	56	56	333	1370
4	1287	17	.765	985	289	0	39	60	60	325	1407
5	1287	16	.745	959	309	0	39	65	63	316	1447
6	1287	15	.720	927	334	0	39	71	67	306	1492
7	1287	14	.700	901	360	0	39	76	71	297	1536
8	1287	13	.670	862	389	0	39	82	75	284	1588
9	1287	12	.640	824	420	0	39	89	80	272	1643
10	1287	11	.610	785	454	0	39	96	84	259	1701
11	1287	10	.575	740	490	0	39	104	90	244	1766
12	1287	9	.540	695	529	0	39	112	95	229	1833
13	1287	8	.500	644	572	0	39	121	101	213	1907
14	1287	7	.450	579	618	0	39	131	107	191	1991
15	1287	6	.400	515	668	0	39	141	113	170	2078
16	1287	5	.350	450	721	0	39	152	120	149	2170
17	1287	4	.290	373	779	0	39	164	127	123	2273
18	1287	3	.230	296	841	0	39	178	135	98	2382
19	1287	2	.160	206	908	0	39	192	143	68	2501
20	1287	1	.085	109	981	0	39	207	151	36	2629

[2] Annual mortgage payment from LCA-1, line N
[4] See Figure 15-5
[5] Column [2] x column [4]
[6] First year cost from worksheet LCA-1:
(C) x (1 - E) x (J.1)
Second and future years:
(first year cost) x (1 + fuel inflation rate)
[7] See line P, worksheet LCA-1

[8] See line R, worksheet LCA-1
[9] First year cost see line S, worksheet LCA-1
Second and future years:
(previous year cost) x (1 + fuel inflation rate)
[10] First year cost see line T, worksheet LCA-1
Second and future years:
(previous year cost) x (1 + general inflation rate)
[11] Column [5] x (Q.3, worksheet LCA-1)
[12] Downpayment + [2]+[6]+[7]+[8]+[9]+[10]-[11]

Worksheet LCA-1

LIFE CYCLE COST ANALYSIS
BASIC DATA

BUILDING DATA (see worksheet TA-1)
- A. Building annual heat load (in million Btu) 90 (m Btu)
- B. Service hot water load (in million Btu) 24.8 (m Btu)
- C. Total annual load 114.8 (m Btu)

SOLAR SYSTEM DATA (see worksheet TA-2)
- D. Collector area 600 (ft^2)
- E. Fraction of annual load carried by solar .85 (%/100)
- F. Unit cost of solar system installed 25 ($/ft^2)
- G. Installed cost of solar system (D x F) 600 x 25 1500 ($)
- H. Type of auxiliary heaters:
  - H.1 Space Electric resistance
  - H.2 Service hot water Electric
- I. Efficiencies of auxiliary heaters:
  - I.1 Space 1.00 (%/100)
  - I.2 Service hot water 1.00 (%/100)
- J. Auxiliary energy costs (see Figures 15-1, 15-2)
  - J.1 Space 9.00 ($/m Btu)
  - J.2 Service hot water 9.00 ($/m Btu)

FINANCIAL DATA
- K. Terms of loan: Years 20 Interest rate 9 (%/100)
- L. Down payment on loan: (10 %/100 x G 15000) 1500 ($)
- M. Amount of loan: G - L 13500 ($)
- N. Annual mortgage payment
  Factor from Figure 15-4 0.11 x M 1485 ($/year)

TAXES AND INSURANCE
- P. Property tax: G 15000 x P.1 .30 x P.2 0.62 279 ($/year)
  - P.1 Ratio of taxable value to installed cost .45 (%/100)
  - P.2 Property tax rate .062 (%/100)
- Q. Income tax rate:
  - Q.1 Federal tax rate .30 (%/100)
  - Q.2 State tax rate .08 (%/100)
  - Q.3 Effective tax rate[(Q.1 + Q.2 - 2(Q.1)(Q.2)] .33 (%/100)
- R. Insurance: [G 15000 x Insurance rate .003 (%/100)] 45 ($/year)

OPERATION AND MAINTENANCE
- S. Operating cost first year:
  (S.1 x S.2 x J.1) 97.6 m Btu x .06 x 9 $/m Btu 53 ($/year)
  - S.1 Annual solar heat supplied (E x C)
    .85 x 114.8 = 97.6 (m Btu)
  - S.2 Fraction of solar for electricity .06 (%/100)
- T. Maintenance cost first year 50 ($/year)

NON SOLAR SYSTEM DATA
- U. Fuel expenses in first year:
  - U.1 Space (A x J.1) ($/year)
  - U.2 Service hot water: (B x J.2) ($/year)
  - U.3 Total load (U.1 + U.2) ($/year)
- V. Operating expenses in first year (U.3 x 0.03) ($/year)
- W. Fuel plus operating expenses in first year (U.3 + V) 1064 ($/year)

LIFE CYCLE COST ANALYSIS
CASH FLOW

A. Mortgage interest rate .09 %/100
B. Auxiliary fuel inflation rate .08 %/100
C. General inflation rate .06 %/100

Collector area 600 ft^2
Solar fraction of total load .85 %/100
(use worksheet TA-2)

System Cost $ 15,000
Down Payment $ 1,500

[1] Year	[2] Annual Mortgage Payment	[3] Years Left on Mortgage	[4] Frac. of Mortgage as Interest	[5] Interest Paid	[6] Auxiliary Fuel Cost	[7] Property Tax	[8] Insurance	[9] Operating Cost	[10] Maintenance Cost	[11] Income Tax Savings	[12] Expense with Solar
1	1485	20	.820	1218	155	0	45	53	50	402	2886
2	1485	19	.805	1195	167	0	45	57	53	394	1413
3	1485	18	.785	1166	181	0	45	62	56	385	1444
4	1485	17	.765	1136	195	0	45	67	60	375	1477
5	1485	16	.745	1106	211	0	45	72	63	365	1511
6	1485	15	.720	1069	228	0	45	78	67	353	1550
7	1485	14	.700	1040	246	0	45	84	71	343	1588
8	1485	13	.670	995	266	0	45	91	75	328	1634
9	1485	12	.640	950	287	0	45	98	80	314	1681
10	1485	11	.610	906	310	0	45	106	84	299	1731
11	1485	10	.575	854	335	0	45	114	90	282	1787
12	1485	9	.540	802	361	0	45	124	95	265	1845
13	1485	8	.500	743	390	0	45	133	101	245	1909
14	1485	7	.450	668	422	0	45	144	107	220	1983
15	1485	6	.40	594	455	0	45	156	113	196	2058
16	1485	5	.35	520	492	0	45	168	121	172	2138
17	1485	4	.29	431	531	0	45	182	127	142	2228
18	1485	3	.23	342	574	0	45	196	135	113	2322
19	1485	2	.16	238	619	0	45	212	143	79	2425
20	1485	1	.085	126	669	0	45	229	151	42	2537

[2] Annual mortgage payment from LCA-1, line N
[4] See Figure 15-5
[5] Column [2] x column [4]
[6] First year cost from worksheet LCA-1:
(C) x (1 - E) X (J.1)
Second and future years:
(first year cost) x (1 + fuel inflation rate)
[7] See line P, worksheet LCA-1
[8] See line R, worksheet LCA-1
[9] First year cost see line S, worksheet LCA-1
Second and future years:
(previous year cost) x (1 + fuel inflation rate)
[10] First year cost see line T, worksheet LCA-1
Second and future years:
(previous year cost) x (1 + general inflation rate)
[11] Column [5] x (Q.3, worksheet LCA-1)
[12] Downpayment + [2]+[6]+[7]+[8]+[9]+[10]-[11]

LIFE CYCLE COST ANALYSIS
ECONOMIC SUMMARY

A. Fuel inflation rate .08 (%/100)

[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]
Year	NON-SOLAR SYSTEM	SOLAR SYSTEM								
		Collector area 400 ft²			Collector area 500 ft²			Collector Area 600 ft²		
	Fuel Plus Operating Expense	Expense with Solar from LCA-2	Savings with Solar [2] - [3]	Cumul. Savings with Solar	Expense with Solar from LCA-2	Savings with Solar [2] - [3]	Cumul. Savings with Solar	Expense with Solar from LCA-2	Savings with Solar [2] - [3]	Cumul. Savings with Solar
1	1064	2314	−1250	−1250	2603	−1539	−1539	2886	−1822	−1822
2	1149	1272	−123	−1373	1334	−185	−1724	1413	−264	−2086
3	1241	1315	−74	−1447	1370	−129	−1853	1444	−203	−2289
4	1340	1360	−20	−1467	1407	−67	−1920	1477	−137	−2426
5	1448	1408	40	−1427	1447	1	−1919	1511	−63	−2489
6	1563	1462	101	−1326	1492	71	−1848	1550	13	−2476
7	1688	1517	171	−1155	1536	152	−1696	1588	100	−2376
8	1824	1579	245	−910	1588	236	−1460	1634	190	−2186
9	1969	1645	324	−586	1643	326	−1134	1681	288	−1898
10	2127	1715	412	−174	1701	426	−708	1731	396	−1502
11	2297	1793	504	330	1766	531	−177	1787	510	−992
12	2481	1875	606	936	1833	648	471	1845	636	−356
13	2679	1964	715	1651	1907	772	1243	1909	770	414
14	2894	2062	832	2483	1991	903	2146	1983	911	911
15	3125	2167	958	3441	2078	1047	3193	2058	1067	1978
16	3375	2280	1095	4536	2170	1205	4398	2138	1237	3215
17	3645	2403	1242	5778	2273	1372	5770	2228	1417	4632
18	3937	2533	1404	7182	2382	1555	7325	2322	1615	6247
19	4252	2677	1575	8757	2501	1751	9076	2425	1827	8074
20	4592	2830	1762	10,519	2629	1963	11,039	2537	2055	10,129

[2] First year cost, see line W of worksheet LCA-1
Second and future year:
(previous year cost) x (1 + fuel inflation rate)
[3] Column [12], worksheet LCA-2
[4] Column [2] - column [3]

[6] Column [12], worksheet LCA-2
[7] Column [2] - column [6]
[9] Column [12], worksheet LCA-2
[10] Column [2] - column [9]

WORKSHEET TA-3

SOLAR SYSTEM SIZE

A. Type of System Air

B. Economical Collector Area 500 ft^2

C. Collector Tilt 55 degrees

D. Collector Fluid Flow Rate:

1. Air System (1.5 to 2 cfm/ft^2 collector) 1000 cfm
2. Liquid System (0.02 gpm/ft^2 collector) N/A gpm

E. Pumps: Liquid System

1. Collector loop flow rate (D.2) N/A gpm
   Head N/A ft
2. Storage loop flow rate (1.5 x E.1) N/A gpm
   Head N/A ft
3. Service water preheater 3 gpm
   Head 2-3 ft
4. Heat distribution coil (depends upon heat delivery rate) N/A gpm
   Head N/A ft

F. Blowers: Air System

1. Collector loop (D.1) 1000 cfm
   Head 1-1.5 in w.g.
2. Distribution blower (provided with furnace) N/A cfm
   Head ____ in w.g.
3. One blower system (D.1) 1000 cfm
   Head 1-1.5 in w.g.

G. Storage:

1. Liquid system B x 2.0 $gallons/ft^2$ collector N/A gal
2. Air system B x 1/2 ft^3/ft^2 collector 250 ft^3
   (a) Pebble size (1-in. screened concrete aggregate)
   (b) Cross-section area (D.1 : 20) 50 ft^2
   (c) Rock depth (G.2 : G.2.b) 5 ft

H. Heat Exchangers:

Consult heat exchanger manufacturer

BLANK WORKSHEET FORMS

Worksheet TA-1
Sheet 1 of 2

Building Heat Load Calculations

Job ______________________________ Number of Occupants______
Computed by______________________ Date____________________
Location_________________________ Latitude________________

Indoor temperature, T_R, ________________°F
Design winter outdoor temperature, T_O, _____°F
Design temperature difference ____________°F
Design degree-day, 65 - T_O, ______________°F

Building Dimensions:
Above Grade: Length_____ft Width_____ft Ceiling Height_____ft
Below Grade: Length_____ft Width_____ft Depth______________ft
Concrete Floor Slab: Exposed perimeter_____ft

Exterior Wall Area: ____
____

Window Area: ____
____

Door Area: ____
____

Net Exterior Wall Area: ____
____

Ceiling Area: ____
____

Floor Area: ____
____

Basement Wall Area: ____
____

Heating Degree-Days:* January __________°F-days
Annual __________°F-days

* From Table 13-2

Worksheet TA-1
Sheet 2 of 2

		U Btu (hr)(ft)(°F)	A	ΔT °F (T_R - T_O)	h = U A ΔT Btu/hr
Exterior Walls (net)					
Basement Walls	Above grade				
	Below grade			*	
Windows and Sliding Patio Doors	Single				
	Double				
	Triple				
	Storm				
Exterior Slab Doors					
Walls, Windows, and Doors					
Floors	Over Crawlspace				
	Concrete Slab on Grade				
	Basement				
Ceiling					
Subtotal (walls, windows, doors, floors, ceiling)					
Infiltration: (0.018) x ________ ft³ x ________ °F					
Duct = 10% of subtotal (if ducts not in insulation envelope)					
Design Heating Load: Btu/hr					
Design Heating Load: Btu/DD Design Heating Load (Btu/hr) X (24 hr/Design DD)					
January Heating Load: m Btu (Btu/DD) X (January DD)					
Annual Heating Load: m Btu (Btu/DD) X (Annual DD)					

* ΔT = T_R - 45°

DOMESTIC HOT WATER LOAD

Number of occupants X 16,680 Btu/day	
January Load (m Btu) (Btu/day) x 31 x 10^{-6}	
Annual Load (m Btu) (January load x 12)	

Worksheet TA-2

SOLAR SYSTEM DATA

Building Owner: ________________________________
Address: ________________________________
Contractor: ________________________________
Type of Solar System (air or liquid) ____________

A. Location: Nearest city ____________________ Latitude (ℓ) ________

B. Mean daily solar radiation in January (s) ____________ ($Btu/ft^2 \cdot day$)

C. January solar radiation on a horizontal surface (S)
($B \times 31$) = ____________ ($Btu/ft^2 \cdot month$)

D. January building heat load (L) ________________ (Btu/month)

E. January solar radiation ÷ January building load
($S \div L$) = ____________ ($1/ft^2$)

F. Collector tilt _________: ℓ + _______ or ℓ - _______

G. Collector Orientation _________ degrees, ____________ from south

H. Heat Exchanger Temperature Difference (Liquid systems only) ______ ^oF

I. Fraction of annual heating load:

[1] Trial Number	[2] Trial Collector Area at Tilt = Latitude A	[3] Area Corrected for Tilt A	[4] Area Corrected for Orientation A	[5] Area Corrected for Heat Exchanger A	[6] $\frac{SA}{L}$	[7] f

[2] Selected arbitrarily or determined from f
[3] Correction to column [2] for tilt not equal to latitude (Fig. 14-2)
[4] Correction to column [3] for orientation (Fig. 14-3)
[5] Correction to column [4] for heat exchanger (liquid systems only)
[6] From Figure 14-1
[7] Selected arbitrarily or determined from Figure 14-1

SOLAR SYSTEM DATA

Building Owner: ______________________

Address: ______________________

Contractor: ______________________

Type of Solar System (air or liquid) __________

A. Location: Nearest city ______________ Latitude (ℓ) ______

B. Mean daily solar radiation in January (s) __________ (Btu/ft^2·day)

C. January solar radiation on a horizontal surface (S)

(B x 31) = __________ (Btu/ft^2·month)

D. January building heat load (L) ______________ (Btu/month)

E. January solar radiation ÷ January building load

(S ÷ L) = __________ (1/ft^2)

F. Collector tilt ________: ℓ + ______ or ℓ - ______

G. Collector Orientation ________ degrees, __________ from south

H. Heat Exchanger Temperature Difference (Liquid systems only) ______ °F

I. Fraction of annual heating load:

[1] Trial Number	[2] Trial Collector Area at Tilt = Latitude A	[3] Area Corrected for Tilt A	[4] Area Corrected for Orientation A	[5] Area Corrected for Heat Exchanger A	[6] $\frac{SA}{L}$	[7] f

[2] Selected arbitrarily or determined from f

[3] Correction to column [2] for tilt not equal to latitude (Fig. 14-2)

[4] Correction to column [3] for orientation (Fig. 14-3)

[5] Correction to column [4] for heat exchanger (liquid systems only)

[6] From Figure 14-1

[7] Selected arbitrarily or determined from Figure 14-1

Worksheet LCA-1

LIFE CYCLE COST ANALYSIS
BASIC DATA

BUILDING DATA (see worksheet TA-1)
A. Building annual heat load (in million Btu) ______(m Btu)
B. Service hot water load (in million Btu) ______(m Btu)
C. Total annual load ______(m Btu)

SOLAR SYSTEM DATA (see worksheet TA-2)
D. Collector area ______(ft^2)
E. Fraction of annual load carried by solar ______(%/100)
F. Unit cost of solar system installed ______($/$ft^2$)
G. Installed cost of solar system (D x F) ______ x ______ ______($)
H. Type of auxiliary heaters:
H.1 Space ______________
H.2 Service hot water ________
I. Efficiencies of auxiliary heaters:
I.1 Space ______________(%/100)
I.2 Service hot water ________(%/100)
J. Auxiliary energy costs (see Figures 15-1, 15-2)
J.1 Space ______________($/m Btu)
J.2 Service hot water ________($/m Btu)

FINANCIAL DATA
K. Terms of loan: Years______ Interest rate______(%/100)
L. Down payment on loan: (______%/100 x G ______) ______($)
M. Amount of loan: G - L ______($)
N. Annual mortgage payment
Factor from Figure 15-4 ______ x M ______($/year)

TAXES AND INSURANCE
P. Property tax: G______ x P.1 ______ x P.2 ______ ______($/year)
P.1 Ratio of taxable value to installed cost ________(%/100)
P.2 Property tax rate ________(%/100)
Q. Income tax rate:
Q.1 Federal tax rate ________(%/100)
Q.2 State tax rate ________(%/100)
Q.3 Effective tax rate[(Q.1 + Q.2 - 2(Q.1)(Q.2)] ______(%/100)
R. Insurance: [G ______ x Insurance rate ______ (%/100)] ______($/year)

OPERATION AND MAINTENANCE
S. Operating cost first year:
(S.1 x S.2 x J.1) ______ m Btu x ______
x ______ $/m Btu ______($/year)
S.1 Annual solar heat supplied (E x C)
______ x ______ = ______(m Btu)
S.2 Fraction of solar for electricity ______ (%/100)
T. Maintenance cost first year ______($/year)

NON SOLAR SYSTEM DATA
U. Fuel expenses in first year:
U.1 Space (A ______ x J.1 ______) ______($/year)
U.2 Service hot water: (B ______ x J.2 ______) ______($/year)
U.3 Total load (U.1 + U.2) ______($/year)
V. Operating expenses in first year (U.3 x 0.03) ______($/year)
W. Fuel plus operating expenses in first year (U.3 + V) ______($/year)

Worksheet LCA-1

LIFE CYCLE COST ANALYSIS
BASIC DATA

BUILDING DATA (see worksheet TA-1)

A. Building annual heat load (in million Btu) ______(m Btu)
B. Service hot water load (in million Btu) ______(m Btu)
C. Total annual load ______(m Btu)

SOLAR SYSTEM DATA (see worksheet TA-2)

D. Collector area ______(ft^2)
E. Fraction of annual load carried by solar ______(%/100)
F. Unit cost of solar system installed ______($/$ft^2$)
G. Installed cost of solar system (D x F) ______ x ______ ______($)
H. Type of auxiliary heaters:
  H.1 Space ____________________
  H.2 Service hot water __________
I. Efficiencies of auxiliary heaters:
  I.1 Space ____________________(%/100)
  I.2 Service hot water __________(%/100)
J. Auxiliary energy costs (see Figures 15-1, 15-2)
  J.1 Space ____________________($/m Btu)
  J.2 Service hot water __________($/m Btu)

FINANCIAL DATA

K. Terms of loan: Years ______ Interest rate ______(%/100)
L. Down payment on loan: (______%/100 x G ______) ______($)
M. Amount of loan: G - L ______($)
N. Annual mortgage payment
  Factor from Figure 15-4 ______ x M ______($/year)

TAXES AND INSURANCE

P. Property tax: G ______ x P.1 ______ x P.2 ______ ______($/year)
  P.1 Ratio of taxable value to installed cost __________(%/100)
  P.2 Property tax rate __________(%/100)
Q. Income tax rate:
  Q.1 Federal tax rate __________(%/100)
  Q.2 State tax rate __________(%/100)
  Q.3 Effective tax rate[(Q.1 + Q.2 - 2(Q.1)(Q.2)] ______(%/100)
R. Insurance: [G ______ x Insurance rate ______ (%/100)] ______($/year)

OPERATION AND MAINTENANCE

S. Operating cost first year:
  (S.1 x S.2 x J.1) ______ m Btu x ______
  x ______ $/m Btu ______($/year)
  S.1 Annual solar heat supplied (E x C)
  ______ x ______ = ______(m Btu)
  S.2 Fraction of solar for electricity ______ (%/100)
T. Maintenance cost first year ______($/year)

NON SOLAR SYSTEM DATA

U. Fuel expenses in first year:
  U.1 Space (A ______ x J.1 ______) ______($/year)
  U.2 Service hot water: (B ______ x J.2 ______) ______($/year)
  U.3 Total load (U.1 + U.2) ______($/year)
V. Operating expenses in first year (U.3 x 0.03) ______($/year)
W. Fuel plus operating expenses in first year (U.3 + V) ______($/year)

Worksheet LCA-1

LIFE CYCLE COST ANALYSIS
BASIC DATA

BUILDING DATA (see worksheet TA-1)
A. Building annual heat load (in million Btu) ______(m Btu)
B. Service hot water load (in million Btu) ______(m Btu)
C. Total annual load ______(m Btu)

SOLAR SYSTEM DATA (see worksheet TA-2)
D. Collector area ______(ft^2)
E. Fraction of annual load carried by solar ______(%/100)
F. Unit cost of solar system installed ______$(\$/\text{ft}^2)$
G. Installed cost of solar system (D x F) ______ x ______ ______($)
H. Type of auxiliary heaters:
H.1 Space ______________
H.2 Service hot water ______________
I. Efficiencies of auxiliary heaters:
I.1 Space ______________(%/100)
I.2 Service hot water ______________(%/100)
J. Auxiliary energy costs (see Figures 15-1, 15-2)
J.1 Space ______________($/m Btu)
J.2 Service hot water ______________($/m Btu)

FINANCIAL DATA
K. Terms of loan: Years ______ Interest rate ______(%/100)
L. Down payment on loan: (______%/100 x G ______) ______($)
M. Amount of loan: G - L ______($)
N. Annual mortgage payment
Factor from Figure 15-4 ______ x M ______($/year)

TAXES AND INSURANCE
P. Property tax: G ______ x P.1 ______ x P.2 ______ ______($/year)
P.1 Ratio of taxable value to installed cost ______________(%/100)
P.2 Property tax rate ______________(%/100)
Q. Income tax rate:
Q.1 Federal tax rate ______________(%/100)
Q.2 State tax rate ______________(%/100)
Q.3 Effective tax rate[(Q.1 + Q.2 - 2(Q.1)(Q.2)] ______(%/100)
R. Insurance: [G ______ x Insurance rate ______ (%/100)] ______($/year)

OPERATION AND MAINTENANCE
S. Operating cost first year:
(S.1 x S.2 x J.1) ______ m Btu x ______
x ______ $/m Btu ______($/year)
S.1 Annual solar heat supplied (E x C)
______ x ______ = ______(m Btu)
S.2 Fraction of solar for electricity ______ (%/100)
T. Maintenance cost first year ______($/year)

NON SOLAR SYSTEM DATA
U. Fuel expenses in first year:
U.1 Space (A ______ x J.1 ______) ______($/year)
U.2 Service hot water: (B ______ x J.2 ______) ______($/year)
U.3 Total load (U.1 + U.2) ______($/year)
V. Operating expenses in first year (U.3 x 0.03) ______($/year)
W. Fuel plus operating expenses in first year (U.3 + V) ______($/year)

Worksheet LCA-1

LIFE CYCLE COST ANALYSIS
BASIC DATA

BUILDING DATA (see worksheet TA-1)

A. Building annual heat load (in million Btu) ______(m Btu)
B. Service hot water load (in million Btu) ______(m Btu)
C. Total annual load ______(m Btu)

SOLAR SYSTEM DATA (see worksheet TA-2)

D. Collector area ______(ft^2)
E. Fraction of annual load carried by solar ______(%/100)
F. Unit cost of solar system installed ______(\$/ft^2)
G. Installed cost of solar system (D x F) ______ x ______ ______($)
H. Type of auxiliary heaters:
  H.1 Space ______
  H.2 Service hot water ______
I. Efficiencies of auxiliary heaters:
  I.1 Space ______(%/100)
  I.2 Service hot water ______(%/100)
J. Auxiliary energy costs (see Figures 15-1, 15-2)
  J.1 Space ______($/m Btu)
  J.2 Service hot water ______($/m Btu)

FINANCIAL DATA

K. Terms of loan: Years ______ Interest rate ______(%/100)
L. Down payment on loan: (______%/100 x G ______) ______($)
M. Amount of loan: G - L ______($)
N. Annual mortgage payment
  Factor from Figure 15-4 ______ x M ______($/year)

TAXES AND INSURANCE

P. Property tax: G ______ x P.1 ______ x P.2 ______ ______($/year)
  P.1 Ratio of taxable value to installed cost ______(%/100)
  P.2 Property tax rate ______(%/100)
Q. Income tax rate:
  Q.1 Federal tax rate ______(%/100)
  Q.2 State tax rate ______(%/100)
  Q.3 Effective tax rate[(Q.1 + Q.2 - 2(Q.1)(Q.2)] ______(%/100)
R. Insurance: [G ______ x Insurance rate ______ (%/100)] ______($/year)

OPERATION AND MAINTENANCE

S. Operating cost first year:
  (S.1 x S.2 x J.1) ______ m Btu x ______
  x ______ $/m Btu ______($/year)
  S.1 Annual solar heat supplied (E x C)
  ______ x ______ = ______(m Btu)
  S.2 Fraction of solar for electricity ______ (%/100)
T. Maintenance cost first year ______($/year)

NON SOLAR SYSTEM DATA

U. Fuel expenses in first year:
  U.1 Space (A ______ x J.1 ______) ______($/year)
  U.2 Service hot water: (B ______ x J.2 ______) ______($/year)
  U.3 Total load (U.1 + U.2) ______($/year)
V. Operating expenses in first year (U.3 x 0.03) ______($/year)
W. Fuel plus operating expenses in first year (U.3 + V) ______($/year)

Worksheet LCA-2

LIFE CYCLE COST ANALYSIS
CASH FLOW

A. Mortgage interest rate ________%/100
B. Auxiliary fuel inflation rate ______%/100
C. General inflation rate __________%/100

Collector area _______________ft^2
Solar fraction of total load ______%/100
(use worksheet TA-2)

System Cost $__________
Down Payment $__________

[1] Year	[2] Annual Mortgage Payment	[3] Years Left on Mortgage	[4] Frac. of Mortgage as Interest	[5] Interest Paid	[6] Auxiliary Fuel Cost	[7] Property Tax	[8] Insurance	[9] Operating Cost	[10] Maintenance Cost	[11] Income Tax Savings	[12] Expense with Solar
1											
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20											

[2] Annual mortgage payment from LCA-1, line N
[4] See Figure 15-5
[5] Column [2] x column [4]
[6] First year cost from worksheet LCA-1:
(C) x (1 - E) X (J.1)
Second and future years:
(first year cost) x (1 + fuel inflation rate)
[7] See line P, worksheet LCA-1
[8] See line R, worksheet LCA-1
[9] First year cost see line S, worksheet LCA-1
Second and future years:
(previous year cost) x (1 + fuel inflation rate)
[10] First year cost see line T, worksheet LCA-1
Second and future years:
(previous year cost) x (1 + general inflation rate)
[11] Column [5] x (Q.3, worksheet LCA-1)
[12] Downpayment + [2]+[6]+[7]+[8]+[9]+[10]-[11]

Worksheet LCA-2

LIFE CYCLE COST ANALYSIS
CASH FLOW

A. Mortgage interest rate ________ %/100
B. Auxiliary fuel inflation rate ________ %/100
C. General inflation rate ________ %/100

Collector area ________ ft^2
Solar fraction of total load ________ %/100
(use worksheet TA-2)

System Cost $ ________
Down Payment $ ________

[1] Year	[2] Annual Mortgage Payment	[3] Years Left on Mortgage	[4] Frac of Mortgage as Interest	[5] Interest Paid	[6] Auxiliary Fuel Cost	[7] Property Tax	[8] Insurance	[9] Operating Cost	[10] Maintenance Cost	[11] Income Tax Savings	[12] Expense with Solar
1											
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[2] Annual mortgage payment from LCA-1, line N
[4] See Figure 15-5
[5] Column [2] x column [4]
[6] First year cost from worksheet LCA-1:
(C) x (1 - E) X (J.1)
Second and future years:
(first year cost) x (1 + fuel inflation rate)
[7] See line P, worksheet LCA-1

[8] See line R, worksheet LCA-1
[9] First year cost see line S, worksheet LCA-1
Second and future years:
(previous year cost) x (1 + fuel inflation rate)
[10] First year cost see line T, worksheet LCA-1
Second and future years:
(previous year cost) x (1 + general inflation rate)
[11] Column [5] x (Q.3, worksheet LCA-1)
[12] Downpayment + [2]+[6]+[7]+[8]+[9]+[10]-[11]

Worksheet LCA-2

LIFE CYCLE COST ANALYSIS
CASH FLOW

A. Mortgage interest rate ________%/100
B. Auxiliary fuel inflation rate ________%/100
C. General inflation rate ________%/100

Collector area ________________ft^2
Solar fraction of total load ______%/100
(use worksheet TA-2)

System Cost $__________
Down Payment $__________

[1] Year	[2] Annual Mortgage Payment	[3] Years Left on Mortgage	[4] Frac. of Mortgage as Interest	[5] Interest Paid	[6] Auxiliary Fuel Cost	[7] Property Tax	[8] Insurance	[9] Operating Cost	[10] Maintenance Cost	[11] Income Tax Savings	[12] Expense with Solar
1											
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[2] Annual mortgage payment from LCA-1, line N
[4] See Figure 15-5
[5] Column [2] x column [4]
[6] First year cost from worksheet LCA-1:
(C) x (1 - E) X (J.1)
Second and future years:
(first year cost) x (1 + fuel inflation rate)
[7] See line P, worksheet LCA-1
[8] See line R, worksheet LCA-1
[9] First year cost see line S, worksheet LCA-1
Second and future years:
(previous year cost) x (1 + fuel inflation rate)
[10] First year cost see line T, worksheet LCA-1
Second and future years:
(previous year cost) x (1 + general inflation rate)
[11] Column [5] x (Q.3, worksheet LCA-1)
[12] Downpayment + [2]+[6]+[7]+[8]+[9]+[10]-[11]

Worksheet LCA-2

LIFE CYCLE COST ANALYSIS
CASH FLOW

A. Mortgage interest rate ________%/100
B. Auxiliary fuel inflation rate ______%/100
C. General inflation rate ________%/100

Collector area ______________ft^2
Solar fraction of total load ______%/100
(use worksheet TA-2)

System Cost $________
Down Payment $________

[1] Year	[2] Annual Mortgage Payment	[3] Years Left on Mortgage	[4] Frac. of Mortgage as Interest	[5] Interest Paid	[6] Auxiliary Fuel Cost	[7] Property Tax	[8] Insurance	[9] Operating Cost	[10] Maintenance Cost	[11] Income Tax Savings	[12] Expense with Solar
1											
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13											
14											
15											
16											
17											
18											
19											
20											

[2] Annual mortgage payment from LCA-1, line N
[4] See Figure 15-5
[5] Column [2] x column [4]
[6] First year cost from worksheet LCA-1:
(C) x (1 - E) X (J.1)
Second and future years:
(first year cost) x (1 + fuel inflation rate)
[7] See line P, worksheet LCA-1
[8] See line R, worksheet LCA-1
[9] First year cost see line S, worksheet LCA-1
Second and future years:
(previous year cost) x (1 + fuel inflation rate)
[10] First year cost see line T, worksheet LCA-1
Second and future years:
(previous year cost) x (1 + general inflation rate)
[11] Column [5] x (Q.3, worksheet LCA-1)
[12] Downpayment + [2]+[6]+[7]+[8]+[9]+[10]-[11]

Worksheet LCA-3

LIFE CYCLE COST ANALYSIS
ECONOMIC SUMMARY

A. Fuel inflation rate ________(%/100)

[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]
Year	NON-SOLAR SYSTEM	SOLAR SYSTEM								
		Collector area _____ ft^2			Collector area _____ ft^2			Collector Area _____ ft^2		
	Fuel Plus Operating Expense	Expense with Solar from LCA-2	Savings with Solar [2] - [3]	Cumul. Savings with Solar	Expense with Solar from LCA-2	Savings with Solar [2] - [3]	Cumul. Savings with Solar	Expense with Solar from LCA-2	Savings with Solar [2] - [3]	Cumul. Savings with Solar
1										
2										
3										
4										
5										
6										
7										
8										
9										
10										
11										
12										
13										
14										
15										
16										
17										
18										
19										
20										

[2] First year cost, see line W of worksheet LCA-1
Second and future year:
(previous year cost) x (1 + fuel inflation rate)
[3] Column [12], worksheet LCA-2
[4] Column [2] - column [3]

[6] Column [12], worksheet LCA-2
[7] Column [2] - column [6]
[9] Column [12], worksheet LCA-2
[10] Column [2] - column [9]

Worksheet LCA-3

LIFE CYCLE COST ANALYSIS
ECONOMIC SUMMARY

A. Fuel inflation rate _______ (%/100)

[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]
Year	NON-SOLAR SYSTEM	SOLAR SYSTEM								
		Collector area _____ ft^2			Collector area _____ ft^2			Collector Area _____ ft^2		
	Fuel Plus Operating Expense	Expense with Solar from LCA-2	Savings with Solar [2] - [3]	Cumul. Savings with Solar	Expense with Solar from LCA-2	Savings with Solar [2] - [3]	Cumul. Savings with Solar	Expense with Solar from LCA-2	Savings with Solar [2] - [3]	Cumul. Savings with Solar
1										
2										
3										
4										
5										
6										
7										
8										
9										
10										
11										
12										
13										
14										
15										
16										
17										
18										
19										
20										

[2] First year cost, see line W of worksheet LCA-1
Second and future year:
(previous year cost) x (1 + fuel inflation rate)
[3] Column [12], worksheet LCA-2
[4] Column [2] - column [3]

[6] Column [12], worksheet LCA-2
[7] Column [2] - column [6]
[9] Column [12], worksheet LCA-2
[10] Column [2] - column [9]

WORKSHEET TA-3

SOLAR SYSTEM SIZE

A. Type of System ______________

B. Economical Collector Area ______________ ft^2

C. Collector Tilt ______________ degrees

D. Collector Fluid Flow Rate:

1. Air System (1.5 to 2 cfm/ft^2 collector) ______________ cfm
2. Liquid System (0.02 gpm/ft^2 collector) ______________ gpm

E. Pumps: Liquid System

1. Collector loop flow rate (D.2) ______________ gpm
   Head ______________ ft
2. Storage loop flow rate (1.5 x E.1) ______________ gpm
   Head ______________ ft
3. Service water preheater 3 gpm
   Head 2-3 ft
4. Heat distribution coil (depends upon heat delivery rate) ______________ gpm
   Head ______________ ft

F. Blowers: Air System

1. Collector loop (D.1) ______________ cfm
   Head 1-1.5 in w.g.
2. Distribution blower (provided with furnace) ______________ cfm
   Head ______________ in w.g.
3. One blower system (D.1) ______________ cfm
   Head 1-1.5 in w.g.

G. Storage:

1. Liquid system B x 2.0 gallons/ft^2 collector ______________ gal
2. Air system B x 1/2 ft^3/ft^2 collector ______________ ft^3
   (a) Pebble size (1-in. screened concrete aggregate)
   (b) Cross-section area (D.1 ÷ 20) ______________ ft^2
   (c) Rock depth (G.2 ÷ G.2.b) ______________ ft

H. Heat Exchangers:

Consult heat exchanger manufacturer

WORKSHEET TA-3

SOLAR SYSTEM SIZE

A. Type of System ______________

B. Economical Collector Area ______________ ft^2

C. Collector Tilt ______________ degrees

D. Collector Fluid Flow Rate:

1. Air System (1.5 to 2 cfm/ft^2 collector) ______________ cfm
2. Liquid System (0.02 gpm/ft^2 collector) ______________ gpm

E. Pumps: Liquid System

1. Collector loop flow rate (D.2) ______________ gpm
   Head ______________ ft
2. Storage loop flow rate (1.5 x E.1) ______________ gpm
   Head ______________ ft
3. Service water preheater 3 gpm
   Head 2-3 ft
4. Heat distribution coil (depends upon heat delivery rate) ______________ gpm
   Head ______________ ft

F. Blowers: Air System

1. Collector loop (D.1) ______________ cfm
   Head 1-1.5 in w.g.
2. Distribution blower (provided with furnace) ______________ cfm
   Head ______________ in w.g.
3. One blower system (D.1) ______________ cfm
   Head 1-1.5 in w.g.

G. Storage:

1. Liquid system B x 2.0 gallons/ft^2 collector ______________ gal
2. Air system B x 1/2 ft^3/ft^2 collector ______________ ft^3
   (a) Pebble size (1-in. screened concrete aggregate)
   (b) Cross-section area (D.1 : 20) ______________ ft^2
   (c) Rock depth (G.2 : G.2.b) ______________ ft

H. Heat Exchangers:

Consult heat exchanger manufacturer

TRAINING COURSE IN
THE PRACTICAL ASPECTS OF
SIZING, INSTALLATION, AND OPERATION OF SOLAR HEATING AND COOLING SYSTEMS
FOR
RESIDENTIAL BUILDINGS

MODULE 17

COST EFFECTIVENESS OF ENERGY CONSERVATION

SOLAR ENERGY APPLICATIONS LABORATORY
COLORADO STATE UNIVERSITY
FORT COLLINS, COLORADO

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INTRODUCTION

Rising energy prices is a strong incentive to reduce energy consumption, and a way to conserve energy in buildings is to reduce heat losses. There are many ways this can be done, the most direct being to provide more insulation in walls and ceilings of new buildings, reduce window area, and use double pane windows and storm doors. While these energy conserving measures are obvious, there are physical and economic limits beyond which energy conserving measures are not effective. This module concerns the cost effectiveness of practical energy conservation measures in residential buildings that provide economic returns on invested capital.

OBJECTIVE

The objective of the trainee is to recognize the merits of specific energy conservation measures in residential buildings and their effect on the economics of solar heating and cooling systems. At the end of this module the trainee should know:

1. The amount of insulation that should be placed in buildings, walls and ceiling
2. The effectiveness of storm windows, doors and multiple glazing to reduce heat losses
3. The effectiveness of lowering the thermostat by two degrees in winter
4. The impact of energy conservation measures on solar heating and cooling systems.

ENERGY CONSERVATION MEASURES

OVERALL HOUSE DESIGN

The arrangement and orientation of a house can strongly influence the energy requirements of the house. For example, changing the shape of a house can change the heat loss rate. A one story house with outside dimensions of 32 x 50 feet can have a heat loss rate as much as 700 Btuh less than a house having dimensions of 25 x 64 feet, even though both have the same floor area, wall insulation (R-11) and window area. A reduction of wall height from 8 feet to 7-1/2 feet for the 32 x 50-foot house can result in a further reduction of about 450 Btuh. An L, T, or H shaped house requires more heating energy than a rectangular house because of greater wall area for the same floor area. A 24 x 50-foot house with a 20 x 20 foot L has the same floor area as the 32 x 50-foot house but there can be a greater heat loss rate by as much as 1000 Btuh.

Locating an unheated garage or a blocking wall on the side of the house toward the prevailing wind (usually the north or northwest) can reduce the winter heating load when the wind is blowing. A similar effect can be obtained by planting natural windbreaks. A protected entrance way to the building or an air lock entrance can also reduce energy needs.

WINDOWS AND DOORS

The window area for many houses is about 15% of the floor area. If this can be reduced to 10% there will be reduction in both initial glass cost and heat loss rate. With double pane windows, heat losses can be reduced by as much as 3000 Btuh. Reduction in window area can be achieved by raising the sill height without sacrificing the view or lighting. As much as 25 to 30 percent of the heat loss from the house occurs through doors and windows. The use of storm doors and windows will reduce this loss by 50 percent.

WALL CONSTRUCTION AND INSULATION

Walls constructed with 2 x 4 studs on 16-in centers have space for 3 1/2 inches of R-11 insulation. By framing the wall with 2 x 6 studs on 24" centers, insulation can be increased to R-19, with 40 percent reduction in heat loss rate. New types of sheathing are available with an insulation value of R-5. In older homes where there is often no wall insulation, mineral wool or similar material can be blown in to achieve an insulating value of about R-7.

Basement walls that extend above grade can be insulated on the interior surface by adding furring strips and insulation which can be covered with gypsum board or plywood. In moderate climates, 2 x 2 furring strips with R-7 insulation is effective, and in extremely cold climates, 2 x 4 furring strips with R-11 insulation may be considered.

FLOOR INSULATION

Floors over unvented crawlspace should be insulated along the perimeter walls of the crawlspace. Vapor barrier on the ground will also help to reduce heat losses to the ground. If the crawlspace is vented, insulation should be installed between the joists. Pipes and ducts passing below the floor should be insulated, as the heat should be conserved in delivery and the heat lost from the pipe or duct will not be useful for heating the enclosure.

CEILING INSULATION

Ceiling insulation to R-30 can easily be attained and is recommended. The minimum insulation should be to R-19.

INFILTRATION REDUCTION

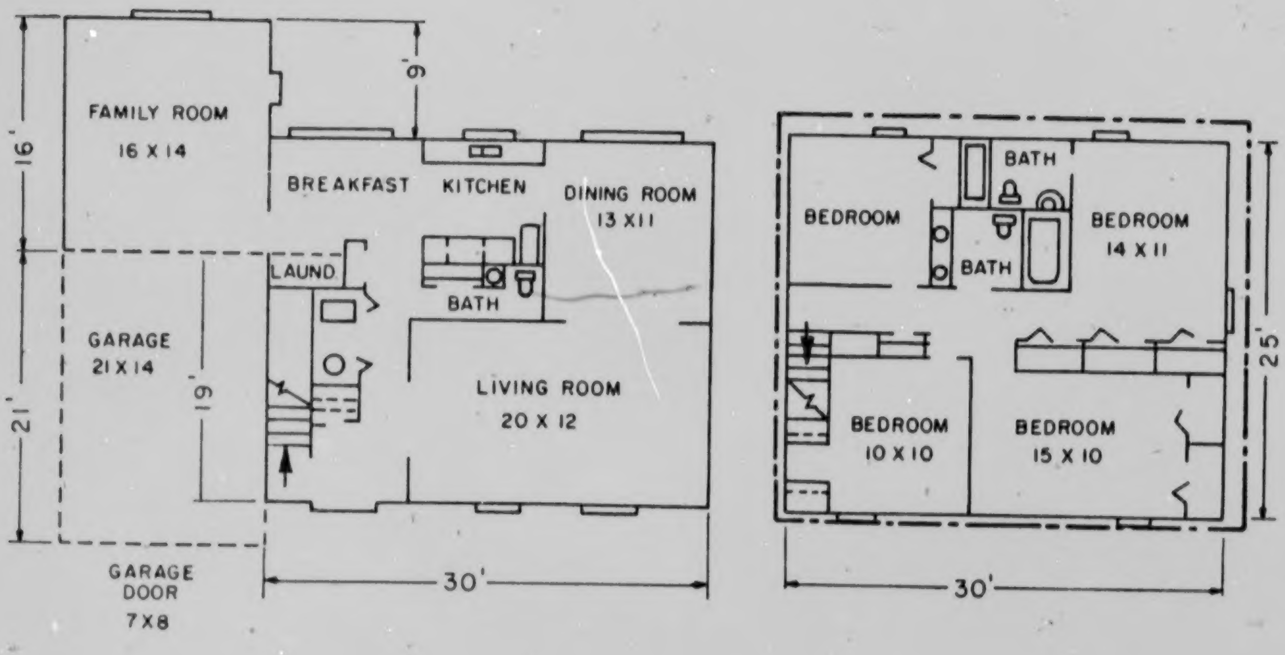
Infiltration of air accounts for half or more of the total heat losses from a building and can be reduced markedly by sealing, caulking and insulating the end plates of the floor joists on the basement walls, around door and window frames and at intersections of walls. The holes around pipes, ducts and wires where they pass through walls and ceilings should be caulked and insulated.

Other ways to reduce infiltration include use of tightly closing flaps on exhaust vents, design fireplaces to draw outside air for combustion, or better still, eliminate fireplaces.

If a building is heated uniformly indoors to 70 °F, reducing the thermostat setting to 68 °F can reduce the heat losses by as much as 2 to 3 percent, depending upon the location. For a building with a heat loss rate of 50,000 Btuh, this can mean a reduction of about 1000 Btuh.

EFFECTIVENESS OF ENERGY CONSERVATION MEASURES

The effectiveness of energy conservation measures is illustrated through calculation of heat losses for a moderate-sized house as shown in Figure 17-1. The house is a simple two-story building and is to be located in a region where the winter heating degree-days is 6000. The calculated heating loads for this example house are listed in Table 17-1 along with basic variations in insulation and types of doors and windows. The design ambient temperature is -10 °F and the indoor temperature is 68 °F.


FAMILY ROOM
16 X 14
16'
9'
BREAKFAST
KITCHEN
DINING ROOM
13 X 11
LAUND.
BATH
GARAGE
21 X 14
21'
19'
LIVING ROOM
20 X 12
GARAGE DOOR
7X8
30'
BATH
BEDROOM
BEDROOM
14 X 11
BATH
25'
BEDROOM
10 X 10
BEDROOM
15 X 10
30'

		Sq. Ft.
Ceiling Area		1621
Wall Area		2335
Window Areas:	North	45
	West	50.5
	South	100
	East	0
		195.5
Door Area		98
Roof Area		1793

Figure 17-1. Example House

Table 17-1. Calculated Heat Loss Rates for the Example House (Figure 17-1)

LINE	WALL INSULATION	CEILING INSULATION	DOORS	WINDOWS	BTUH HEAT LOSS
1	R-0	R-7	Solidwood 1.5 in.	Single glass 100% glass	88,846
2	R-0	R-7	Solidwood 1.5 in.	Single glass 80% glass	87,234
3	R-0	R-7	Solidwood 2.0 in.	Single glass 80% glass	87,073
4	R-0	R-7	Storm metal & 1.5 in. Solidwood	Single glass 80% glass	86,989
5	R-0	R-7	Solidwood 1.5 in.	Double insulating Double glass 80% 3/16 in. air space	82,077
6	R-0	R-7	Solidwood 2.0 in.	Double insulating Double glass 80% 3/16 in. air space	81,916
7	R-0	R-7	Storm metal & 1.5 in. Solidwood	Double glass 80% Double insulating 3/16 in. air space	81,832
8	R-0	R-7	Solidwood 1.5 in.	Triple insulating Triple glass 80% 1/2 in. air space	77,605
9	R-0	R-7	Storm metal & 2.0 in. Solidwood	Triple insulation Triple glass 80% 1/2 in. air space	77,229
10	R-7	R-7	Solidwood 1.5 in.	Single glass 100% glass	66,636
11	R-7	R-7	Solidwood 1.5 in.	Double insulating Double glass 80% 3/16 in. air space	59,867
12	R-7	R-7	Storm metal & 1.5 in. Solidwood	Triple insulating Triple glass 80% 1/2 in. air space	55,149
13	R-7	R-11	Solidwood 1.5 in.	Single glass 80% glass	62,500
14	R-7	R-11	Storm metal & 1.5 in. Solidwood	Single glass 80% glass	62,255

Table 17-1 (continued)

LINE	WALL INSULATION	CEILING INSULATION	DOORS	WINDOWS	BTUH HEAT LOSS
15	R-7	R-11	Solidwood 1.5 in.	Double insulation Double glass 80% 3/16 in. air space	57,343
16	R-7	R-11	Storm metal & 1.5 in. Solidwood	Double insulating Double glass 80% 3/16 in. air space	57,102
17	R-7	R-11	Storm metal & 2.0 in. Solidwood	Triple insulating Triple glass 80% 1/2 in. air space	52,496
18	R-11	R-11	Solidwood 1.5 in.	Single glass Double glass 80% 3/16 in. air space	58,987
19	R-11	R-11	Storm metal & 1.5 in. Solidwood	Double insulating Double glass 80% 3/16 in. air space	53,585
20	R-11	R-11	Storm metal & 2.0 in. Solidwood	Double insulating Single glass 80% Emissivity = 0.2 1/2 in. air space	49,525
21	R-11	R-11	Storm metal & 2.0 in. Solidwood	Triple insulating Triple glass 80% 1/2 in. air space	48,983
22	R-11	R-19	Solidwood 1.5 in.	Single glass 100% glass	58,233
23	R-11	R-19	Solidwood 1.5 in.	Single glass 80% glass	56,621
24	R-11	R-19	Solidwood 1.5 in.	Double insulating Double glass 80% 3/16 in. air space	51,464
25	R-11	R-19	Solidwood 1.5 in.	Double insulating Single glass 80% Emissivity = 0.2 1/2 in. air space	47,534
26	R-11	R-19	Storm metal & 1.5 in. Solidwood	Double insulating Single glass 80% Emissivity 80% 1/2 in. air space	47,288
27	R-11	R-19	Storm metal & 2.0 in. Solidwood	Triple insulating Triple glass 80% 3/16 in. air space	46,616

Table 17-1 (continued)

LINE	WALL INSULATION	CEILING INSULATION	DOORS	WINDOWS	BTUH HEAT LOSS
28	R-0	R-11	Wooden Door 1.5 in.	Single glass 100% glass	86,303
29	R-0	R-19	Wooden Door 1.5 in.	Single glass 100% glass	83,915
30	R-7	R-0	Wooden Door 1.5 in.	Single glass 100% glass	84,698
31	R-7	R-11	Wooden Door 1.5 in.	Single glass 100% glass	64,112
32	R-7	R-19	Wooden Door 1.5 in.	Single glass 100% glass	61,743
33	R-11	R-0	Wooden Door 1.5 in.	Single glass 100% glass	81,165
34	R-11	R-7	Wooden Door 1.5 in.	Single glass 100% glass	63,120
35	R-11	R-11	Wooden Door 1.5 in.	Single glass 100% glass	60,599
36	R-19	R-0	Wooden Door 1.5 in.	Single glass 100% glass	77,748
37	R-19	R-7	Wooden Door 1.5 in.	Single glass 100% glass	59,720
38	R-19	R-11	Wooden Door 1.5 in.	Single glass 100% glass	57,202
39	R-19	R-19	Wooden Door 1.5 in.	Single glass 100% glass	54,838
40	R-0	R-0	Wooden Door 1.5 in.	Single glass 100% glass	107,032
41	R-19	R-40	Wood Storm Doors & 2.0 in. Solidwood Doors	Triple insulating 1/2 in. air space & Storm windows 60% glass-wood sash	40,079

Total Window Area = 195.42 Sq. Ft.
Total Door Area = 98 Sq. Ft.
45° Pitched Roof
No Basement

Consider that the basic design for the house includes R-7 insulation in the walls, R-11 insulation above the ceiling, solid wood doors and single glass windows. The basic design condition is identified by the box in Table 17-1, (line 13), and the calculated heat load is 62,500 Btuh for the design condition.

REDUCTION IN HEAT LOSS RATES

When a double-glazed window replaces the single-glass window (line 15) in the example house, the heat loss rate reduces from 62,500 Btuh to 57,343 Btuh, which is a reduction of 5,160 Btuh. With double glazing and increased ceiling insulation the heat loss rate reduces further to 51,460 Btuh for a total reduction of 11,040 Btuh from the original condition. Other energy conserving features can be compared from the tabulated values. The cost-effectiveness of the energy conservation measure is dependent upon energy cost, rate of energy cost increase, interest and terms of the loan for money borrowed to implement the energy conserving measure, property tax if any, increase in annual insurance premium and savings on income taxes.

ENERGY CONSERVATION COST AND SAVINGS

The methodology for determining the cost and benefits from investments made in energy conservation practices is presented. Using the example building, suppose that the ceiling insulation thickness is increased from 3 1/2 inches to 6 inches, changing the R factor from R-11 to R-19, and the wall insulation is increased from R-7 to R-11. This results in reduction of heat loss rate from 62,500 Btuh (line 13, Table 17-1) to 56,621 Btuh (line 23), or 5879 Btuh, (say 5900 Btuh).

The reduction in heat loss rate will mean a reduction in consumption of energy. The amount of energy saving is determined as follows: The design heating temperature difference is:

$$TD = 68°F - (-10°F) = 78°F;$$

the design heat load for the base design is 62,500 Btu per hour. The heat requirement for degree-day is:

$$\frac{62{,}500}{78} \times 24 = 19{,}300 \text{ Btu/DD.}$$

The reduction in heat loss rate because of the added insulation is (62,500 - 56,621) x 24/78 = 5879 x 24/78 = 1809 Btu per DD. For a heating season with 6240 DD, the savings in energy is:

$$1809 \times 6240 = 11.3 \text{ mBtu.}$$

From Figure 15-2, with electric resistance heating at 3¢/kWh, the heating cost is $8.80 mBtu. The annual dollar savings is:

$$\frac{\$8.80}{\text{mBtu}} \times 11.3 \text{ mBtu} = \$100.$$

The total cost of insulation to effect a savings of $100 annually in heat costs is determined as follows: The extra ceiling insulation of 3 inches is about $\$0.09/ft^2$ including installation, or 0.09 x 1621 = $146 (see Figure 17-1 for ceiling area), and for the walls, the added costs are about $\$0.05/ft^2$, or 0.05 x 2336 = $117. The total added cost for insulation is about $263.

Although in this example it is readily seen that with $100 annual energy cost savings, the added $263 cost for insulation is returned through fuel savings in less than three years, we will continue through with this example to illustrate the economic analysis. Let us assume that the money for insulating was borrowed at seven-percent interest and 15-year loan. The annual repayment factor from Figure 15-4 is 0.11, so that the mortgage payment on the loan is:

$$\text{Annual Mortgage Payment} = 0.11 \times 263 = \$29/\text{yr}$$

In addition to the mortgage, there are property tax and insurance to be paid at an annual rate of, say, 1.5 percent of the added cost or, 0.015 x 263 = $4/year, and there are savings on income taxes for interest paid. Although the credit will decline annually and is dependent upon the income level of the homeowner, assume that the savings on income taxes balance the amount for property tax and insurance.

The ratio of annual savings to annual cost is then:

$$\text{Savings Factor (SF)} = \frac{\$100}{\$29} = 3.4$$

If the energy cost increases, the savings factor will increase.

While in this example the ratio of the benefit in annual savings to cost of the added insulation is large, there are some energy conservation measures where the benefit/cost ratio may be less than one. Obviously such energy conservation measures should not be implemented.

ENERGY CONSERVATION AND SOLAR SYSTEMS

To determine the effect of energy conservation on solar system size, an economic analysis must be made on the basis of a smaller annual heating load, using the procedure discussed in Module 15. We will use the example house in Figure 17-1 and consider the effect of energy conservation with a simplified economic analysis. With R-7 insulation in the walls and R-11 insulation in the ceiling, the heat load is 19,230 Btu/DD. With 6240 DD during the heating season, the total heat required during the season is:

$$19{,}230 \ \frac{\text{Btu}}{\text{DD}} \times 6240 \text{ DD} = 120 \ \text{mBtu.}$$

A solar air heating system with 500 square feet of collector can be reasonably expected to provide 70 percent of the heating load for the assumed location. Thus, the initial cost with 24/ft^2 installed collector area will be $12,000. Assume that a 20-year loan is secured at 8 percent interest with 20 percent down payment.

The annual mortgage payment on the $9,600 loan is (.102 x 9600)$979/yr. The annual operating cost for the solar system is $60 with electricity at 4¢/kWh. The balance of the heat load must be provided by electricity at 4¢/kWh, or $11.85 per m Btu, and it will cost $427 annually to provide the auxiliary heat with the solar system:

$$120 \text{ m Btu} \times (1-0.7) \times \frac{\$11.85}{\text{m Btu}} = \$427/\text{yr.}$$

Thus the first year cost for solar plus auxiliary electric heat is $3866 with the downpayment and $1466 without the downpayment. Maintenance cost, property tax and insurance are assumed to be offset by income tax savings. A 6 percent inflation rate is assumed.

With the added insulation, the heat loss rate reduces to 18,100 Btu per DD. The total heat load for a 6000 DD season is:

$$18100 \ \frac{\text{Btu}}{\text{DD}} \times 6000 \text{ DD} = 108.6 \text{ m Btu.}$$

There are two ways to view the effect on the solar system. One is to maintain the same collector area which will obviously provide greater percentage of solar contribution to total load and reduction in auxiliary energy, and the other is to reduce the collector area to provide about the same fraction of the total load as before, i.e., 70 percent.

NO REDUCTION IN COLLECTOR AREA

With no reduction in collector area, there should result a reduction in auxiliary fuel consumption by 11.4 m Btu. With auxiliary energy cost at $11.85/m Btu, the total cost of auxiliary energy is:

[$427 - (11.85 x 11.4)] = $291.

The annual cost for the energy conservation measure is $29 which must be added to the annual solar and auxiliary energy costs. Thus, the annual costs are:

	First Year with Downpayment	First Year without Downpayment
Solar System Cost	$3379	$ 979
Operating Cost	60	60
Auxiliary Energy Cost	291	291
Energy Conservation Cost	29	29
Total Annual	$3759	$1359

The total annual cost with the energy conservation measure is less than the cost to heat the house with the original design by $107/year.

REDUCED COLLECTOR AREA

With reduction in heat load by 11.4 m Btu, it should be possible to reduce collector area to 450 ft^2 and maintain 70 percent of the annual load. The costs are as follows:

Solar System Cost ($24 x 450 ft^2)	$10800		
Downpayment		$2160	
Annual Mortgage Payment			$881
Operating Cost			54
Auxiliary Energy Cost (108.6 x 0.3 x 11.85)			386
Energy Conservation Cost			29
FIRST YEAR COST WITH DOWNPAYMENT			$3510
FIRST YEAR COST WITHOUT DOWNPAYMENT			$1350

Comparison of the annual costs indicates the reduction of collector area will reduce the first year cost with downpayment by $249, and by $9, not including the downpayment. A summary of costs for solar and non-solar systems is presented in Table 17-2 with an inflation rate of 6 percent applied.

The comparisons after 15 years for savings with conservation in a non-solar system indicate that as much as $2500 might be realized by simply adding insulation at the time of initial house construction. In this example, there is a difference of $2700 after 15 years between a solar system with and without energy conservation measures. The difference clearly indicates that energy conservation with a solar system is economically advantageous.

Table 17-2. Annual Cost for Heating the Example House Based on 4¢/kWh Electricity and 6% Inflation Rate (See text of module for computation details)

	NON SOLAR SYSTEM		SOLAR SYSTEM		
YEAR	NO CONSERVATION	WITH CONSERVATION	NO CONSERVATION A = 500 ft^2	WITH CONSERVATION A = 500 ft^2	WITH CONSERVATION A = 450 ft^2
1	$1422	$1314	$3866	$3759	$3510
2	1507	1393	1495	1380	1376
3	1598	1476	1526	1402	1404
4	1694	1565	1559	1426	1434
5	1795	1659	1594	1451	1465
6	1903	1758	1631	1478	1499
7	2017	1864	1670	1506	1534
8	2138	1976	1711	1536	1572
9	2266	2094	1755	1567	1611
10	2402	2220	1802	1601	1653
11	2547	2353	1851	1637	1698
12	2699	2494	1903	1674	1745
13	2861	2644	1959	1714	1795
14	3033	2803	2018	1757	1848
15	3215	2971	2080	1802	1904
TOTALS	$33097	$30584	$28420	$25690	$26048

Summary of Savings

Non Solar - No Conservation	$33097
Non Solar - With Conservation	30584
Savings with conservation	$ 2513
Solar - No Conservation	$28420
Solar - With Conservation	25690
Savings with Conservation	$ 2730

TRAINING COURSE IN
THE PRACTICAL ASPECTS OF
SIZING, INSTALLATION, AND OPERATION OF SOLAR HEATING AND COOLING SYSTEMS
FOR
RESIDENTIAL BUILDINGS

MODULE 18

RETROFIT CONSIDERATIONS

SOLAR ENERGY APPLICATIONS LABORATORY
COLORADO STATE UNIVERSITY
FORT COLLINS, COLORADO

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INTRODUCTION

Retrofit in the present context means the adaptation of solar systems to existing buildings. There are many owners of residential buildings who are experiencing rising costs for heating, and consequently, a strong interest is developing in retrofitting solar systems to existing structures. Solar system designs for existing buildings are fundamentally the same as for new buildings. However, there are many factors concerning installation that need to be considered in retrofitting; factors that are not involved in new construction. These factors relate to the structural and mechanical features of existing buildings and to the cost of installation. Each installation is a special case and generalizations of problems are difficult. At this stage in development (1976), there have not been many retrofit installations of solar heating and cooling systems for residential buildings.

OBJECTIVE

The objective of this module is to direct the attention of trainees to some of the typical problems that could be encountered in retrofit installations.

GENERAL CONSIDERATIONS

INSULATING EXISTING BUILDINGS

Although insulating a building is not strictly a feature of solar energy systems, it was shown in Module 17 that there is a significant impact on solar systems with energy conservation designs in buildings.

Many existing residential buildings have little or no insulation in the walls and ceilings and the heat loss rate is therefore large. If a solar system is contemplated, an initial step is to insulate the building.

If the cost for adequately insulating the building is high, an economic analysis to determine benefits and cost is recommended.

TREES AND LANDSCAPE

The availability of sunshine for the particular building is of prime importance. There are many existing residential buildings that have been landscaped generously with trees for the specific purpose of shading the building and at least some of the trees will have to be removed. Although solar radiation will filter through leaf-less branches of deciduous trees during the winter, the reduction in useful sunshine could greatly affect the system size and performance. An alternative to removal is to reduce the height, but this will invite an annual or periodic maintenance cost that is chargeable to the solar system.

There are many locations where buildings on hillsides are shaded by neighboring structures. Solar systems for buildings that are in shadow a portion of the day will necessitate an unusual orientation of the collectors with consequent increase in collector area and system cost.

DOMESTIC HOT WATER SYSTEM

Domestic hot water retrofit systems are being considered in many regions of the United States. The types and performance of solar hot water systems that are appropriate for retrofit installation are discussed in detail in Module 7. There is no basic difference in system configuration for new and retrofit construction. However, depending on the site, it may be necessary to situate the collectors away from the building. A schematic arrangement to support collectors that are not mounted on the house is shown in Figure 18-1. The system is applicable for non-freezing climates. The hot water line should be insulated however to reduce thermal losses in transport from the preheat tank to the existing hot water tank. No drains other than the ones on the water tanks are needed for the system. Manual valves are installed in the lines inside the house to isolate the solar system from the conventional system.

A retrofit solar domestic hot water heater in freezing climates is shown in Figure 18-2. In freezing climates, it is advisable to locate the preheat tank inside the building. There will be greater line losses in circulating water through the collector, and provisions for drainage are needed.

The simplest arrangement for retrofitting to electric resistance hot water heaters is shown in Figure 18-3. The system is discussed in Module 7 and is a system that could be used in non-freezing climates.

SPACE HEATING

There are several potential difficulties involved in providing retrofit solar space heating systems. These problems concern:

1. Collector location
2. Equipment location
3. Adaptation to the existing heating system.

COLLECTOR LOCATION

Collectors can be advantageously mounted on the roof of new buildings if the weight of the collectors can be supported. Otherwise, collectors

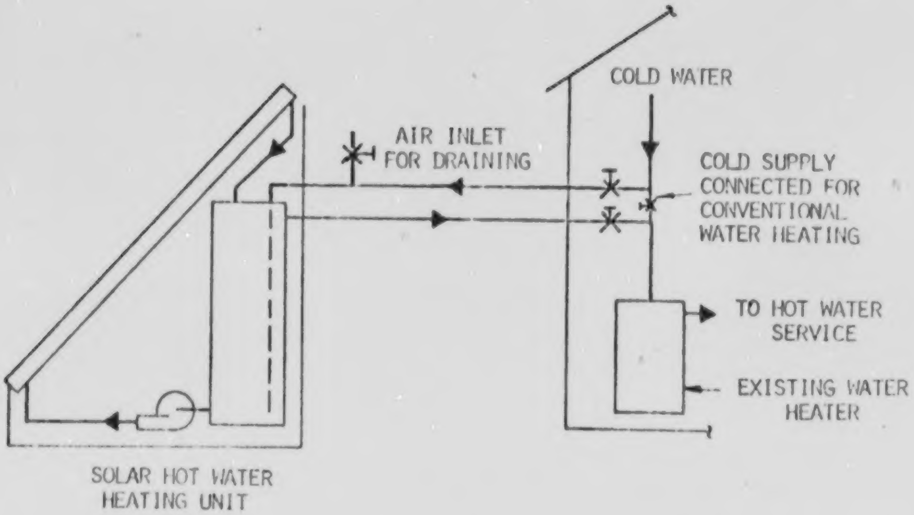
COLD WATER
AIR INLET FOR DRAINING
COLD SUPPLY CONNECTED FOR CONVENTIONAL WATER HEATING
TO HOT WATER SERVICE
EXISTING WATER HEATER
SOLAR HOT WATER HEATING UNIT

Figure 18-1. Retrofit Solar Domestic Hot Water Heater, Non-Freezing Climates

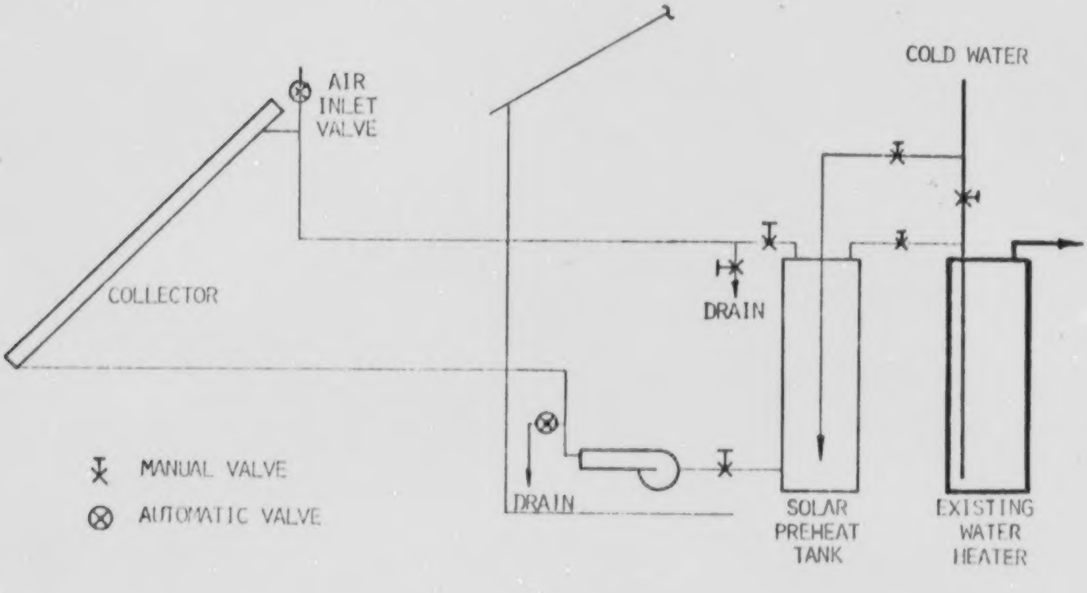
AIR INLET VALVE
COLD WATER
COLLECTOR
DRAIN
MANUAL VALVE
AUTOMATIC VALVE
DRAIN
SOLAR PREHEAT TANK
EXISTING WATER HEATER

Figure 18-2. Retrofit Solar Domestic Hot Water Heater, Freezing Climates

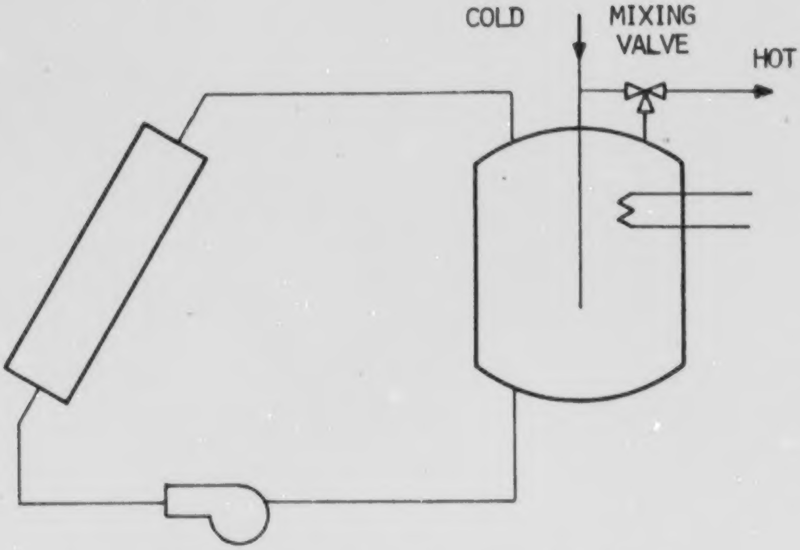

Figure 18-3. Direct Heating Pump Circulation

will have to be supported on a separate structure on the ground. In new construction, the roof pitch is set at the desired collector tilt angle to maximize the collection of solar energy for a particular orientation, but in retrofit situations, the roof pitch normally is 5 on 12, or 22.6° from horizontal. This angle is too flat for solar collectors in most locations so a separate frame is needed to mount the collectors at a more suitable angle. One possible arrangement is shown in Figure 18-4. The "add-on" appearance of the collectors and supports may be aesthetically unsatisfactory to some home owners. When aesthetics govern, either the entire roof must be reconstructed to blend them architecturally with the building, or the collectors must be placed at ground level. Removal and reconstruction are expensive and although there may be beneficial effects in the renovation other than to accommodate collectors, the costs will be chargeable to the solar system.

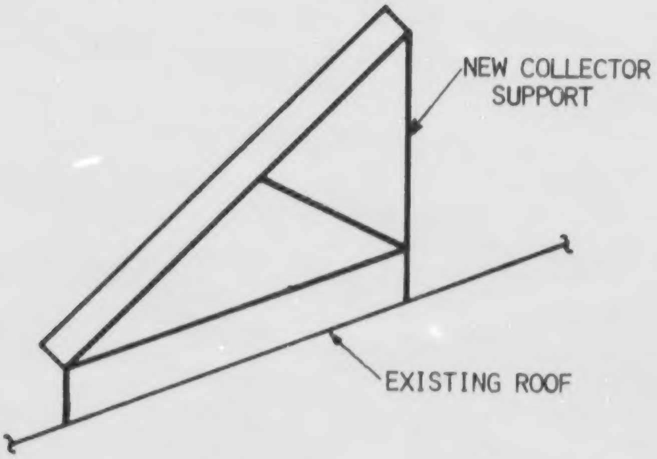

Figure 18-4. Collector Frame Supports on Roof

When collectors cannot be placed on the building roof, they must be placed at ground level and preferably on the south side adjacent to the building. Placing collectors at ground level offers some advantages and some disadvantages. One advantage is lower pumping head. Another is that piping and ducting to the collector banks are easier to install than in the attic of an existing building with a low-pitched roof. Maintenance of collectors at ground level is easier. The disadvantages are that the collector array may offer hazards to the occupants, and pipes and ducts are in unheated areas or exposed to the outside air. Insulation around pipes and ducts must be thick to reduce heat losses.

The location of equipment needed for solar heating and cooling systems may offer difficulties for some retrofit installations. The bulkiest equipment that has to be installed is the storage tank for a hydronic system and a rock bed for an air system. The most easily accessible area in the building is at ground floor level. However, ground floor space is expensive compared to comparable space in the basement or garage.

The fabrication of storage tanks and rock boxes in basements, or placing of rocks in storage,are restrictive activities in retrofit installations. The walls of rock bed storage containers can be fabricated relatively easily, but fabricating tanks for water storage could be more difficult. Tanks may be fabricated inside by either welding or bolting sections together, and if bolted tanks are used, neoprene or butyl rubber lining is recommended to prevent leaks from the bolted seams.

Locating the storage tank or rock bed in the garage offers the simplest installation for retrofit situations. Adaptation to the existing heating system with the storage tank in the garage may require longer pipes and ducts than if storage were located inside the building. The biggest disadvantage with storage located in the garage is that the heat loss from storage is not recovered as useful heat in the building enclosure.

It is recommended that heat exchangers and pumps be located close to the storage tank for hydronic systems to minimize head losses and economize on space. The appurtenant equipment such as pumps and heat exchangers will not occupy much space. Maintenance will also be facilitated if all of the equipment is located in one place.

ADAPTATION TO EXISTING HEATING EQUIPMENT

The solar heating and cooling systems discussed in this manual are for central air distribution systems. Adaptation of solar systems to existing buildings is likewise facilitated if a central distribution system exists. While baseboard heating systems are prevalent in many non-solar hydronic systems, flat-plate collectors will not function well with such systems. Fan coil units are recommended for such retrofit installations.

A difficulty in adapting to an existing air-heating system is illustrated in Figure 18-5. Usually, the blower is an integral part of a furnace. The heating element, whether fuel-fired or electric, is coupled to the blower. The controls must be arranged so that the blower is independent of the heat unit. Whether the blower is after the heating coil, as shown in Figure 18-5, or before, it would not matter, particularly if the motor to drive the blower is outside the duct. The location of the water-to-air heating coil is dependent upon the existing duct arrangement.

An air solar system might be arranged as shown in Figure 18-6. A two-blower system is most suitable for retrofit installations. The existing blower will have to be decoupled from the heating element control as discussed before and the dampers shown in the figure will control the different modes of operation.

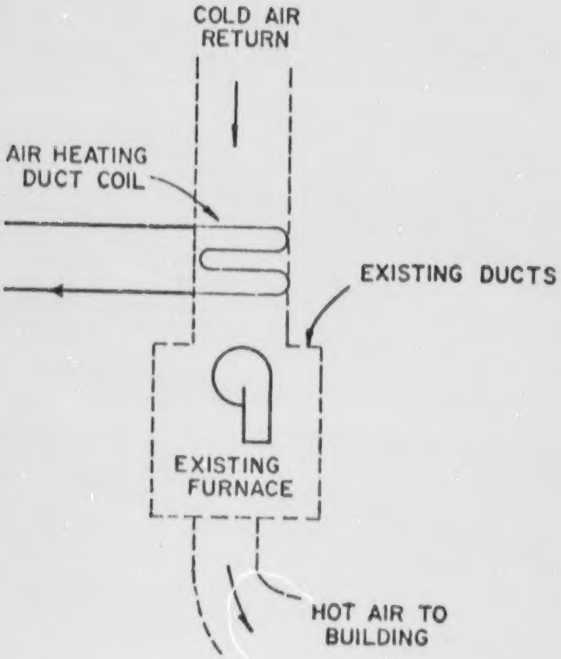
COLD AIR RETURN
AIR HEATING DUCT COIL
EXISTING DUCTS
EXISTING FURNACE
HOT AIR TO BUILDING

Figure 18-5. Hydronic Solar System for Retrofit Installation

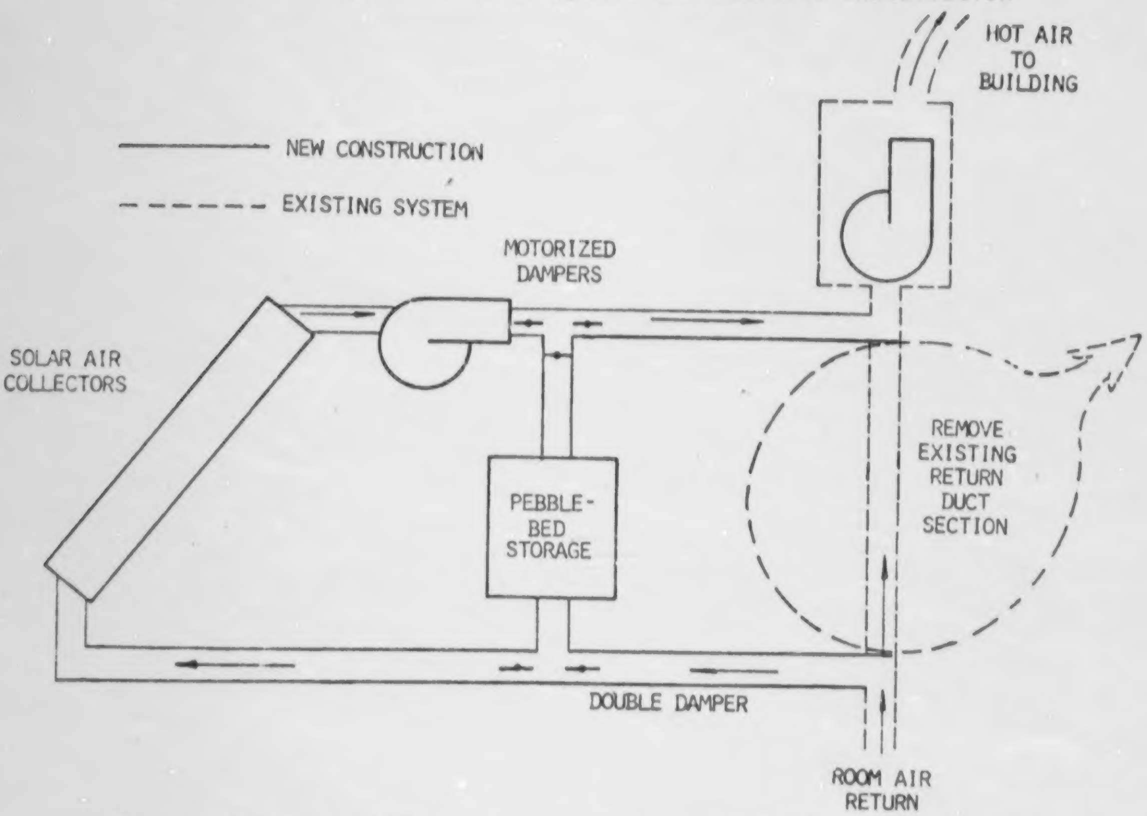
HOT AIR TO BUILDING
NEW CONSTRUCTION
EXISTING SYSTEM
MOTORIZED DAMPERS
SOLAR AIR COLLECTORS
PEBBLE-BED STORAGE
REMOVE EXISTING RETURN DUCT SECTION
DOUBLE DAMPER
ROOM AIR RETURN

Figure 18-6. Air-Heating Solar System for Retrofit Installation

TRAINING COURSE IN

THE PRACTICAL ASPECTS OF

SIZING, INSTALLATION, AND OPERATION OF SOLAR HEATING AND COOLING SYSTEMS

FOR

RESIDENTIAL BUILDINGS

MODULE 19

SCHEDULING OF SOLAR INSTALLATIONS

SOLAR ENERGY APPLICATIONS LABORATORY

COLORADO STATE UNIVERSITY

FORT COLLINS, COLORADO

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INTRODUCTION

The scheduling of sequential and concurrent activities for installing solar heating and/or cooling systems during new home construction depends upon the type of system to be installed. Undoubtedly, standard or simplified critical path schedules are used only for larger construction projects. Nevertheless, two example schedules for constructing typical homes will be followed in this module to trace the sequences of installing solar systems in new home construction. If attention is not given to the sequence of assembly, unnecessarily difficult situations could result, with consequent increase in the total costs for the building construction.

OBJECTIVE

The objective in this module is to familiarize trainees with the important sequences for installation of solar systems in new home construction.

CONSTRUCTION SCHEDULE FOR A TYPICAL HOME WITH AN AIR-HEATING SOLAR SYSTEM

PART 1, ROCK-BED STORAGE

The initial steps in the construction of a home with an air-heating solar system are shown in Figure 19-1. The building contains a basement in this example, and the principal solar system component included in this phase is a storage unit located in the basement. The activities concerning the pebble-bed storage unit are identified by heavy lines from 4 to 6, 6 to 8, 6 to 9, 9 to 11, and 10 to 11.

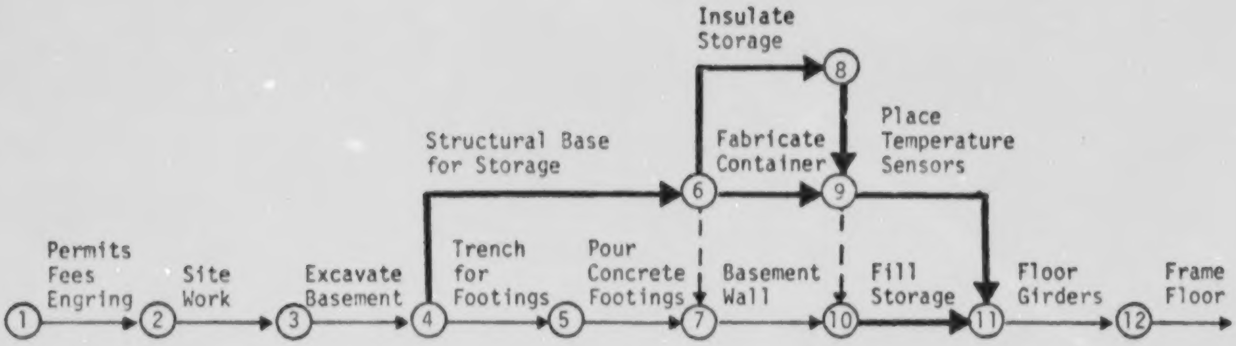

Permits
Fees
Engring
Site
Work
Excavate
Basement
Trench
for
Footings
Pour
Concrete
Footings
Basement
Wall
Fill
Storage
Floor
Girders
Frame
Floor
Structural Base
for Storage
Fabricate
Container
Insulate
Storage
Place
Temperature
Sensors
1
2
3
4
5
6
7
8
9
10
11
12

Figure 19-1. Part 1 - Pebble-Bed Storage Fabrication

The structural base for the rock-bed storage unit should be constructed during the foundation work of the building. The concrete base should be scheduled for pouring along with the concrete footings. If the storage container walls are to be concrete, the rock bed can be located in the corner of the basement to utilize common walls. If the container is to be fabricated of wood, the walls and insulation can be constructed prior to placement of the floor girders and joists.

The placement of temperature sensors for the control system and, if desired, for monitoring purposes, is a simultaneous activity with the filling of the rock bin. It is not practical to install sensors after the gravel has been placed in the bin.

PART 2, COLLECTOR SUPPORTS

The support structure for solar collector modules or panels may be the vertical wall of the building or the roof trusses or rafters. The schedule in Figure 19-2 assumes the collectors are to be placed on the roof, but may be revised as necessary for attachment to the external wall. The spacing between roof trusses, or wall studs, should be convenient for the type of collector to be used in the solar system.

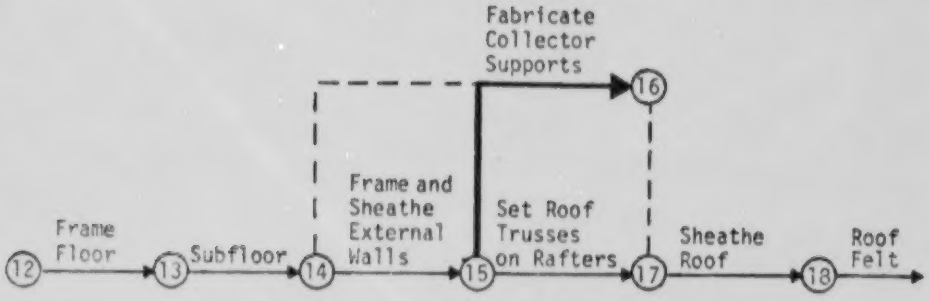

Fabricate Collector Supports
16
Frame Floor
Subfloor
Frame and Sheathe External Walls
Set Roof Trusses on Rafters
Sheathe Roof
Roof Felt
12
13
14
15
17
18

Figure 19-2. Part 2 - Collector Support Construction

Unnecessary consumption of time in mounting collectors can be avoided with forethought given to convenient placement of purlins and nailers. There must be space provided for manifold air ducts which will cross the roof trusses. The roof trusses should be made up of cross-pieces that will support the ducts.

The manifold which delivers air from the collector to storage is usually installed near the ridge of the roof. There should be sufficient space available to facilitate duct installations. Supports for collectors on flat roofs can be an integral part of the rafters, or the collector supports can be mounted above the finished roof.

PART 3, INSTALLATION OF COLLECTORS, PIPING, AND CONTROL PANEL

Installation of collector modules can be scheduled simultaneously with the roofing and flashing. The collectors, in most instances, will replace the roofing, and should be rendered water-tight with cap strips between collector modules and flashing along the top, bottom, and sides of the collector array.

For heavy collector modules, a mechanical hoist such as a fork lift may be needed for installation. Although detailed instructions may be

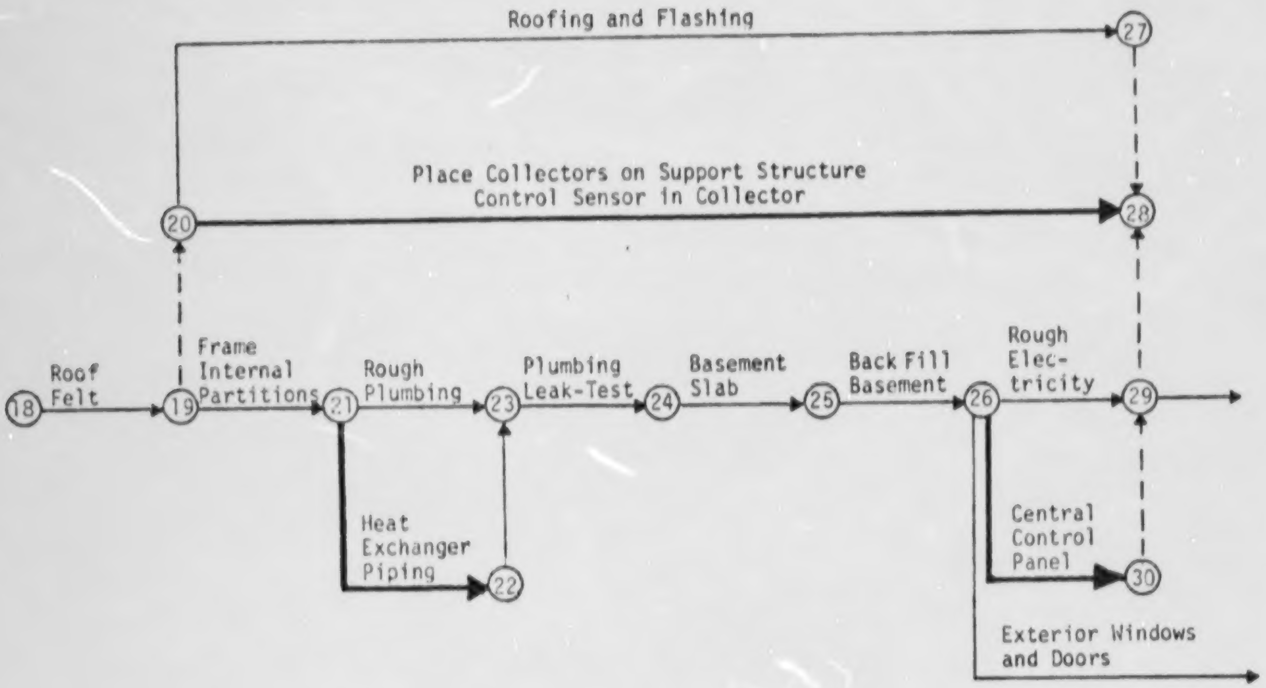

Roofing and Flashing
27
Place Collectors on Support Structure
Control Sensor in Collector
20
28
18
Roof Felt
19
Frame Internal Partitions
21
Rough Plumbing
23
Plumbing Leak-Test
24
Basement Slab
25
Back Fill Basement
26
Rough Elec-tricity
29
Heat Exchanger Piping
22
Central Control Panel
30
Exterior Windows and Doors

Figure 19-3. Part 3 - Collector, Heat Exchanger, and Control Panel Installation

provided by the manufacturer for assembly of collector modules, considerable attention should be given to effect air-tight joints at all duct connections. Air leakage into the collector array can cause loss of heat from the system.

Piping to the air-water heat exchanger may be scheduled with the other building plumbing. All pipes should be leak-tested along with the other pipe joints.

If the control panel for the solar system is a separate unit, the installation can be scheduled with the other rough electrical work. The control panel should be located close to the solar system for convenience.

PART 4, INSULATION

Insulation on piping and ducts can be applied following leak-tests. Insulation should cover valves as well as the piping. Loosely wrapped insulation may allow air circulation and therefore is not effective, but tightly wrapped insulation reduces the thickness, without decreasing conductivity, and is therefore poor practice. All ducts and pipes, whether they are flexible or rigid, should be insulated.

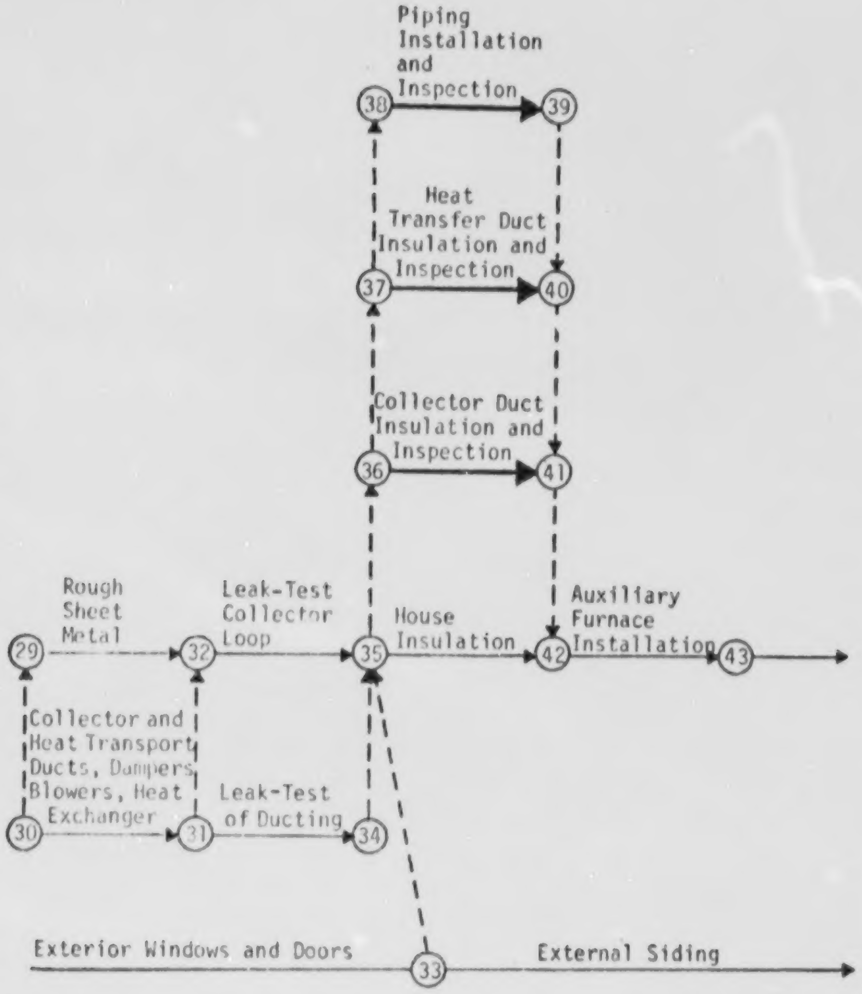

Piping Installation and Inspection
38
39
Heat Transfer Duct Insulation and Inspection
37
40
Collector Duct Insulation and Inspection
36
41
Rough Sheet Metal
29
32
Leak-Test Collector Loop
35
House Insulation
42
Auxiliary Furnace Installation
43
Collector and Heat Transport Ducts, Dampers, Blowers, Heat Exchanger
30
31
Leak-Test of Ducting
34
Exterior Windows and Doors
33
External Siding

Figure 19-4. Part 4 - Application of Insulation

PART 5, PREHEAT TANK INSTALLATION

After the interior of the building has been completed, the preheat tank and domestic hot water tank can be installed and the plumbing finished. Insulation around the piping is recommended to reduce heat losses. While the appliances are being installed, the electrical work can also be completed.

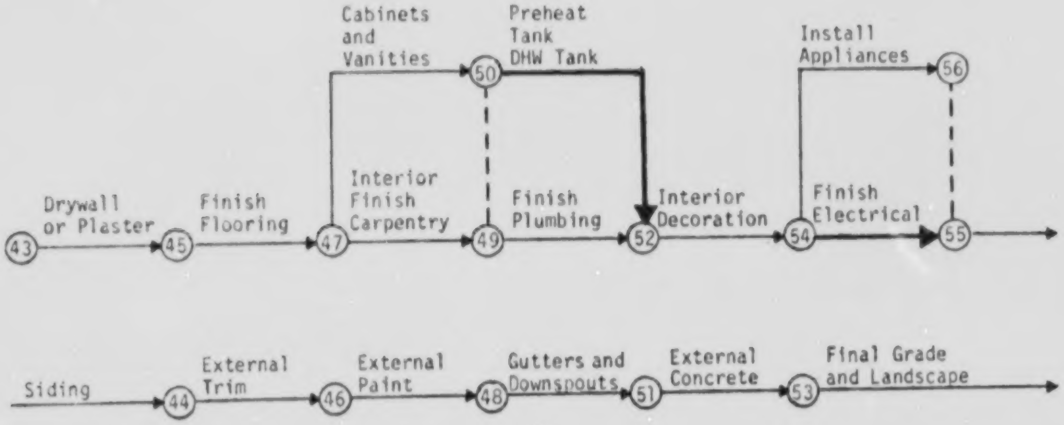

Cabinets and Vanities
Preheat Tank DHW Tank
Install Appliances
50
56
Drywall or Plaster
Finish Flooring
Interior Finish Carpentry
Finish Plumbing
Interior Decoration
Finish Electrical
43
45
47
49
52
54
55
Siding
External Trim
External Paint
Gutters and Downspouts
External Concrete
Final Grade and Landscape
44
46
48
51
53

Figure 19-5. Part 5 - Preheat Tank Installation

PART 6, FINISH THE HEATING SYSTEM AND FINAL INSPECTION

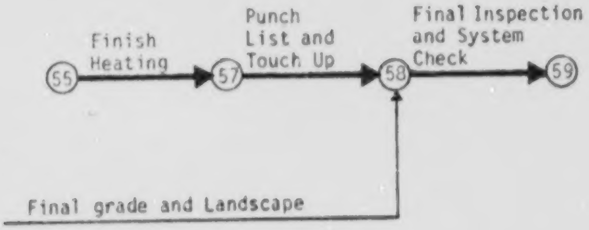

Finish Heating
Punch List and Touch Up
Final Inspection and System Check
55
57
58
59
Final grade and Landscape

Figure 19-6. Part 6 - Finishing and Final Inspection

After the completed installation, the system should be tested using a check list similar to the one included in Module 12 of this manual. The motorized damper mechanisms should be given particular attention. If dampers do not close firmly, there will be leaks into the flow loop and when cold air is mixed with the warm air, considerable temperature degradation can take place. Although heat may not be lost from the system, lowered air temperatures can cause the auxiliary furnace to operate a larger portion of the time. A check of the system and in particular the dampers is advisable after the system has been in operation for a short period of time.

CONSTRUCTION SCHEDULE FOR A TYPICAL HOME WITH A TYPICAL LIQUID-HEATING SOLAR SYSTEM

PART 1, WATER STORAGE TANK

The structural base for the thermal storage unit is provided when the concrete is poured for the footings. The storage requires a thicker concrete slab than the normal four inches poured for basement floors.

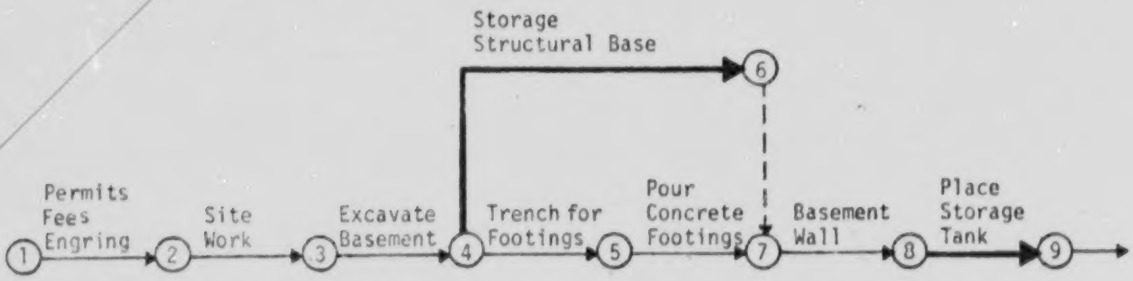

Storage
Structural Base
6
Permits
Fees
Engring
1
Site
Work
2
Excavate
Basement
3
4
Trench for
Footings
5
Pour
Concrete
Footings
7
Basement
Wall
8
Place
Storage
Tank
9

Figure 19-7. Part 1 - Storage Tank Foundation

Tanks are normally prefabricated and when located in basements they should be placed on the base before the floor girders are assembled.

The storage tank should be provided with appropriate connections for pipes and the control sensor, and any connection located on the base of the tank should be attached before the tank is placed on the base. Depending upon the type of storage tank, the bottom insulation should be installed before placement to eliminate extra work at a later time to insulate the tank.

PART 2, COLLECTOR SUPPORTS

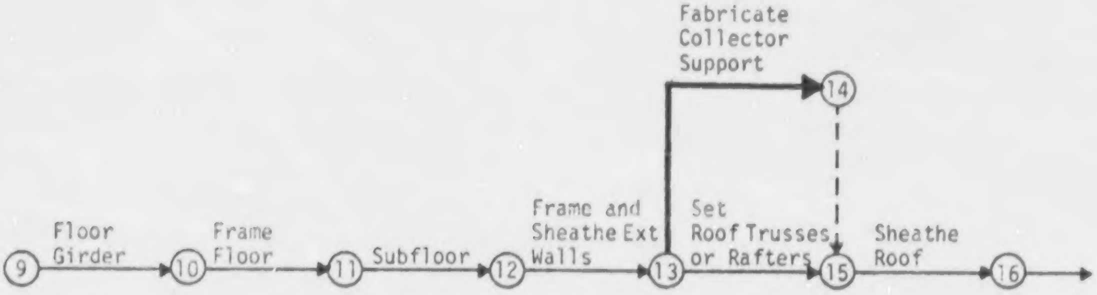

Fabricate Collector Support
14
Floor Girder
Frame Floor
Subfloor
Frame and Sheathe Ext Walls
Set Roof Trusses or Rafters
Sheathe Roof
9
10
11
12
13
15
16

Figure 19-8. Part 2 - Fabricate Collector Support

Normally the rafters are the supports for the collector array; however, special supports may be required for some installations. When rafters are to support the collectors directly, some preplanning will reduce the labor costs to assemble and secure the collectors, particularly if the collectors are supported between the rafters. Normally collectors are mounted on plywood sheathing and the collectors are secured by bolts through the plywood.

Pipe manifolds are normally placed along the ridge and eave of the roof. Provisions for easy access, not only for installation, but also for maintenance should be provided. Replacement of flexible connections between the collector panels and the manifold is a common maintenance item and, although replacement is simple, it can be made difficult with restrictive access, particularly the upper manifold.

Collectors mounted on flat roofs will require supports for tilting the collectors. The supports should be secured to the rafters, and open collector supports should be closed in to prevent wind drag and snow drifting, both of which will add extra loads on the roof.

PART 3, COLLECTOR INSTALLATION AND PIPING

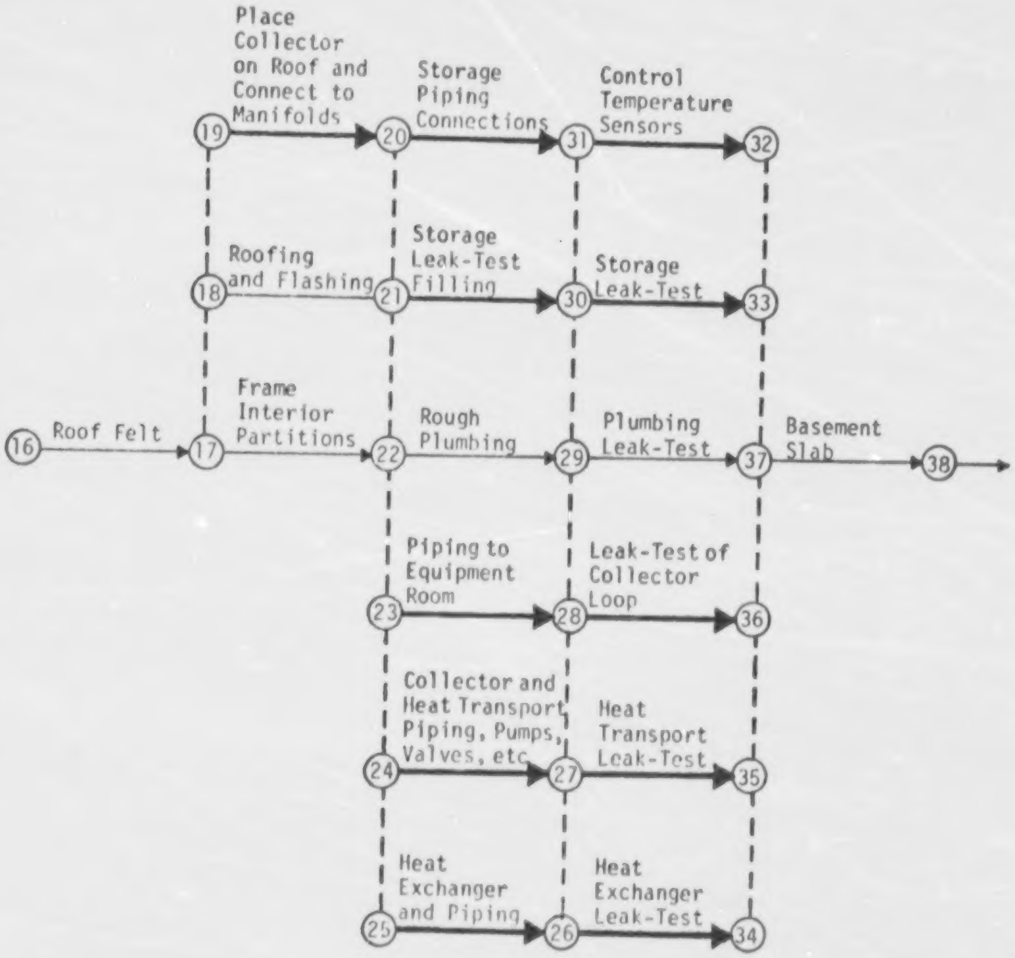

Place Collector on Roof and Connect to Manifolds
Storage Piping Connections
Control Temperature Sensors
19
20
31
32
Roofing and Flashing
Storage Leak-Test Filling
Storage Leak-Test
18
21
30
33
Roof Felt
Frame Interior Partitions
Rough Plumbing
Plumbing Leak-Test
Basement Slab
16
17
22
29
37
38
Piping to Equipment Room
Leak-Test of Collector Loop
23
28
36
Collector and Heat Transport Piping, Pumps, Valves, etc
Heat Transport Leak-Test
24
27
35
Heat Exchanger and Piping
Heat Exchanger Leak-Test
25
26
34

Figure 19-9. Part 3 - Collector Installation and Piping

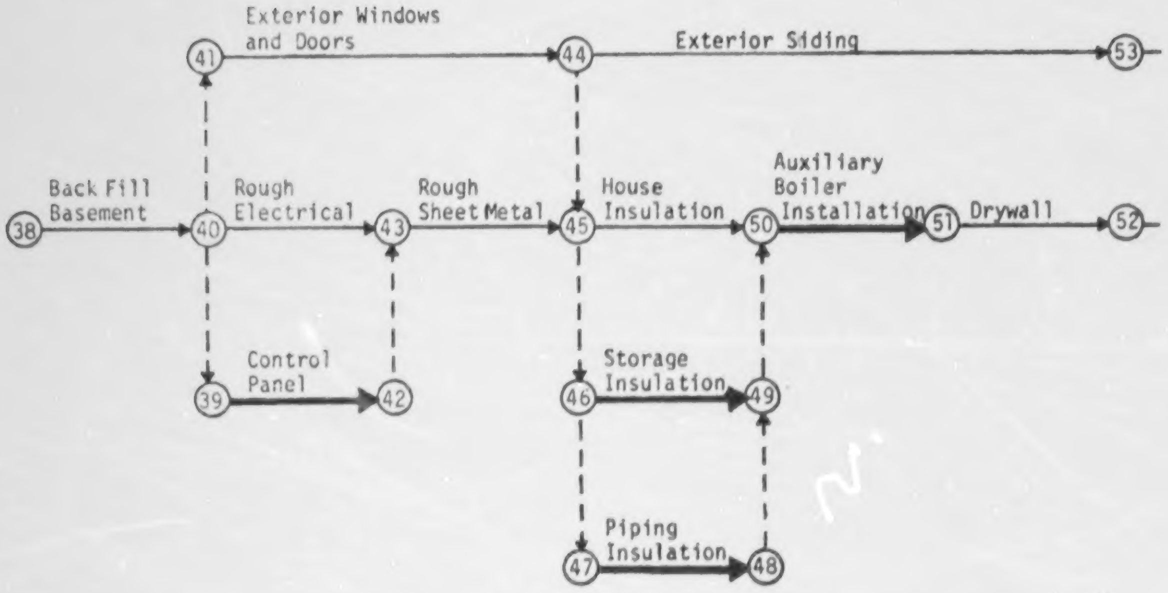
Collectors should be carefully inspected before installation. Broken glass, improper seals, absorber plate conditions, and bad plumbing fittings are easy to identify. There is an advantage in placing liquid collectors tightly together side-by-side to minimize side heat losses from each collector module. When this cannot be done, insulation between the collector modules should be used to reduce the side heat losses. The manifolds should be connected to the collectors as the modules are installed to facilitate the connections. Although flexible connections will probably be used in most installations, the misalignment of a few collector modules can be cumulative,and even flexible hoses may become difficult to install if the collectors and manifold piping are not aligned properly.

The rough plumbing for the house and solar system can be scheduled simultaneously and, after placement of the control sensors, the various pipe loops can be leak-tested. A filter unit, all the valves, the heat exchanger, pumps, and an expansion tank should be installed in the collector loop.

The control temperature sensors can be installed in the storage tank and the collector outlet pipe manifold either before or after the leak tests.

PART 4, INSULATION AND AUXILIARY BOILER

The pipes in the solar system should be insulated to minimize heat loss, and the insulating must be done before drywalling. The storage tank, heat exchanger, and the expansion tank, as well as the valves, should be well insulated.



Exterior Windows and Doors
Exterior Siding
Back Fill Basement
Rough Electrical
Rough Sheet Metal
House Insulation
Auxiliary Boiler Installation
Drywall
Control Panel
Storage Insulation
Piping Insulation
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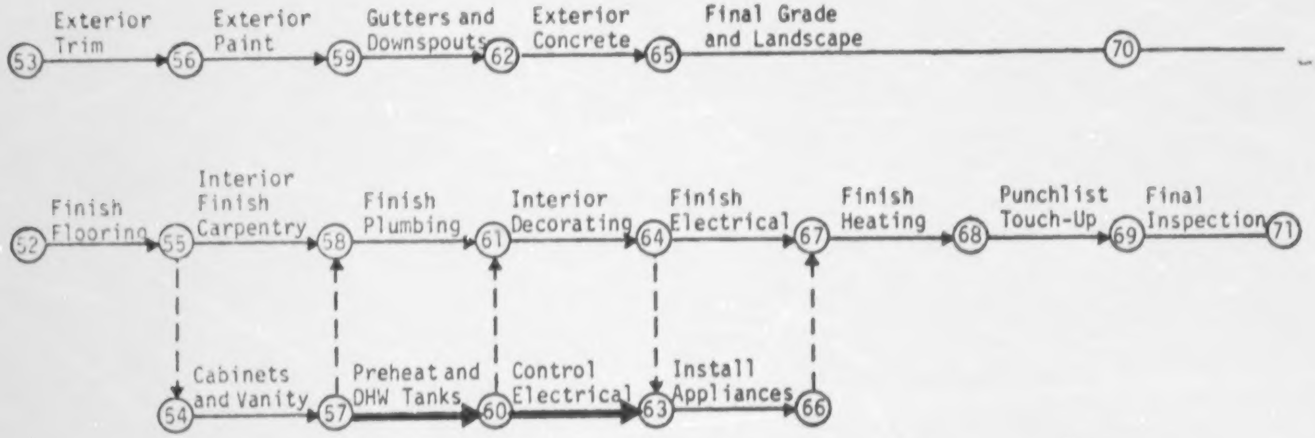
Figure 19-10. Part 4 - Insulation and Auxiliary Boiler

PART 5, PREHEAT TANK AND CONTROL WIRING



Exterior Trim
Exterior Paint
Gutters and Downspouts
Exterior Concrete
Final Grade and Landscape
Finish Flooring
Interior Finish Carpentry
Finish Plumbing
Interior Decorating
Finish Electrical
Finish Heating
Punchlist Touch-Up
Final Inspection
Cabinets and Vanity
Preheat and DHW Tanks
Control Electrical
Install Appliances
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Figure 19-11. Part 5 - Preheat Tank and Control Connections

The preheat tank and control panel wiring are the final items of installation for the solar system. It is recommended that initial tests be made of the solar system and final inspection and tests be made after a short period of operation.

TRAINING COURSE IN
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MODULE 20

CONSTRAINTS AND INCENTIVES

SOLAR ENERGY APPLICATIONS LABORATORY
COLORADO STATE UNIVERSITY
FORT COLLINS, COLORADO

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INTRODUCTION

There are several significant "barriers" to widespread application of solar energy systems in homes, and there are a few incentives that could be created to induce greater use. The greatest barrier to solar system utilization is the lack of understanding of solar heating and cooling systems among homeowners, contractors, engineers, architects, and others in the home building industry. This course is intended to overcome some of the lack in knowledge about solar systems. First cost of systems is another barrier, but understanding the economics of solar systems, and the rising cost for fuel, will assist in overcoming this barrier. Among the greatest incentives for homeowners to install solar systems is to provide substantial credit against first cost. The credits can be for income and property taxes. These and other barriers and incentives are discussed in this module.

OBJECTIVE

The objective of the trainee is to recognize the barriers and incentives for installation of solar heating and cooling systems in residential buildings.

LACK OF UNDERSTANDING

Unless the homeowner is a technically oriented individual, the potential customer for a solar heating system is likely to have little basic understanding of a solar heating and cooling system. The building contractor, or HVAC installer, is given the responsibility of explaining the system, the components, and the performance of systems as compared to standard heating and cooling methods. The knowledge gained from this course can be used effectively by the trainees to explain the kinds of solar systems available and the probable performance of the systems in residential buildings.

The contractor should explain the economic aspects of solar heating and cooling systems -- that, despite high first cost, the cumulative costs after 10 or more years will favor the solar system. It should be emphasized that a solar system can provide the major fraction of the annual heat load, and an auxiliary unit is needed, but the energy consumption and costs are substantially reduced.

INSTITUTIONAL CONSTRAINTS

Solar heating and cooling systems are new to the legal, financial, and insurance institutions and face existing and, perhaps, new institutional constraints. Fortunately, there are few barriers established to constrain installation of solar systems, but characteristically laws are written after problems occur, financial policies are developed after experience is gained, and insurance rates are based on risk factors and probabilities.

LEGAL

Access to Sunlight

An important aspect of solar systems is continued access to sunlight. While zoning can be effective, it is not a guarantee to continued access to sunlight because zoning can change. A high-rise building on the south side of a residence with a solar system can be devastating.

Even if the problem of shading by other structures is avoided, shadows cast by the neighbors' tall trees can be a serious problem. At present, the owner of an adjacent lot can plant any tree he wishes, except if the height may interfere with utility lines. The concept of a solar easement has some merit, but has not been enacted anywhere at this time.

Land Use and Zoning

Land use legislation and zoning restrictions can restrict the usefulness of solar energy systems by regulating the placement of collectors. On the other hand, regulations can also encourage the use of solar systems by requiring street layouts to maximize solar energy use. Restrictive regulations regarding architectural style or materials of construction should be scrutinized. It is difficult, for instance, to build a solar house in a subdivision that allows only shake shingle roofs. Likewise, a restriction on the orientation of a building on the lot could hamper the collector orientation.

Building Codes

There are virtually no building codes in the United States which deal specifically with solar heating systems or components thereof. Some efforts toward establishment of specific codes have been started, but until criteria and standards have been set by national agencies, the information on which local authorities must base their codes for solar equipment is not available.

Most building codes, however, have provisions which can be applied to solar heating equipment as part of the structural and heating components of a building. Requirements as to roof load capability, structural integrity, flammability of material, ventilation requirements, and so on, have restrictive as well as proscriptive influence on solar equipment.

It is therefore necessary for an installer and owner of a solar heating system to comply with such terms in the local codes. In turn, the manufacturer will be required to conform if his hardware is to be sold and used in a particular area. For example, if a local code requires Underwriters Laboratory certification on heating units in a building, the manufacturer and installer would be required to use only such equipment in the solar system.

To the present time, building inspectors appear to have encountered no serious problems in approving solar heating installations. With probably over a thousand solar heating systems in the United States, it is evident that the lack of specific codes on solar heating equipment has not significantly deterred its use.

Since a full-capacity conventional heat supply is required in practically all areas where building codes apply, there is no appreciable danger that a solar heating system would fail to keep a building at a comfortable and safe temperature. Even if the efficiency of a solar heating system is far less than expected, a code authority could still approve such a system without transgressing code requirements.

As a general rule, an owner or contractor planning to install a solar heating system should contact the local building inspector prior to the expenditure of major effort on the project in order that any questions which may relate to compliance with the code could be resolved in advance. If a particular solar heating system or component clearly violated a code requirement, a change to some other type of hardware could be made prior to expenditure of significant funds on a system which would not be acceptable.

FINANCIAL

Financing is available for solar systems from a few lending institutions. Because information about system performance, reliability, and life times is meager, many savings and loan companies do not have established policies. Some loan money for the entire building project, less the down payment, purely on the ability to pay the mortgage. Others restrict loans to projects that include approved solar systems, and still others loan money only on the basis of the type of auxiliary unit that is used in the solar system. If loan companies provide financing only for the building, and not for the solar system, there is a financial barrier to installing solar systems.

INSURANCE

Insurance companies have shown no reluctance to insure solar houses at rates comparable to other houses. There has not been sufficient experience to change the insurance rates for solar houses from non-solar homes.

INCENTIVES

The greatest incentive for solar heating systems is the rising energy cost and the lack of alternatives to electricity for heating. Other incentives are being created in the form of tax relief. For example, several states have reduced or eliminated the property tax assessment on new solar systems and a few states have provided deductions on state income tax returns for owners of solar heating systems in their homes.

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TRAINING COURSE IN
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SIZING, INSTALLATION, AND OPERATION OF SOLAR HEATING AND COOLING SYSTEMS
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MODULE 21

BUYER'S GUIDE

SOLAR ENERGY APPLICATIONS LABORATORY
COLORADO STATE UNIVERSITY
FORT COLLINS, COLORADO

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INTRODUCTION

In addition to understanding the design and operation of solar heating systems, suppliers and users should be acquainted with several other aspects of solar heating. In order that intelligent selection of equipment can be made, knowledge of industry standards, equipment warranties, performance evaluation data, and related topics is necessary. If evaluations have been performed, their results need to be available to the supplier and user. The kinds of data required for such appraisal must be understood. The advantages and the disadvantages of the main system types for a specific application are particularly important. Knowledge of the type of hardware available, their cost, and their compatibility with other components in the system is essential. Such items as safety and durability are additional criteria for equipment evaluation and selection.

Within this module, the main points enumerated above are addressed, and a guide to their consideration is presented. Because of (a) the newness of the solar equipment industry, (b) limited experience in the use of fully commercial systems in non-subsidized installations, (c) lack of criteria for system evaluation and certification, and (d) lack of information on durability, marketability, and other factors, much of the material here outlined is tentative, rapidly changing, and highly variable in time and place. The following information should therefore be considered a guide rather than a set of specifications.

OBJECTIVE

The objective of this module is to provide the trainee with guides to the purchase of equipment for solar heating systems. The reference list of manufacturers of equipment is not intended to be all inclusive. Guidelines for choosing solar equipment and systems are provided, not only in this module, but throughout this manual.

AVAILABILITY OF SYSTEMS AND COMPONENTS

COLLECTORS

A directory of manufacturers and suppliers of solar heating (and cooling) equipment has been published by the U.S. Energy Research and Development Administration under the title, "Catalog on Solar Heating and Cooling Products". Published in November 1975, and designated ERDA-75, it has been updated by the Solar Energy Industries Association. Among scores of organizations listed as manufacturers of solar heating equipment, possibly a dozen firms have supplied or could furnish solar collectors in quantities of thousands of square feet with one- to two-month lead time for delivery. A listing of some firms is shown in Table 21-1. The list is not intended to be complete nor is the inclusion of a firm intended to imply relative usefulness (efficiency, durability, cost, etc.) of the product. The list contains, however, most of the firms having sold collectors, for space heating, to residential users and to the federal government in total quantities of thousands of square feet. The type of collector manufactured and miscellaneous comments are also presented.

Table 21-1
Selected Collector Manufacturers

Name of Firm	Collector Type	Collector Materials
Ametek	Liquid	Copper, glass (1) or (2)
Chamberlain	Liquid	Steel, glass (2)
General Electric	Liquid	Aluminum, lexan (2)
Grumman	Liquid	Copper, glass (2)
Honeywell	Liquid	Copper-steel, glass (2)
Lennox	Liquid	See Honeywell
Owens-Illinois	Liquid	Glass (evacuated tube)
PPG	Liquid	Copper, glass (2)
Revere	Liquid	Copper, glass (2) or (1)
Solaron	Air	Steel, glass (2)
Sunsource	Liquid	
Sunworks	Liquid or air	Copper, glass (1)

CONTROL

In addition to the equipment listed above, another commercially available component is the control system. The special unit in most solar heating control systems is the differential thermostat with its temperature sensors for insertion in collector and storage. Also available are control panels for connection of the differential thermostat, the room thermostat, and the various relays and motor actuators for blowers, pumps, and valves and dampers. The controllers may be of the conventional electromechanical type with bimetallic temperature sensors or thermocouples or thermistors, along with mechanical relays for energizing motors. Also available are solid-state controllers with thermistor and thermocouple inputs and solid-state switches and relays producing appropriate electric outputs to motors. Electromechanical types are more familiar to heating system installers and service personnel, whereas solid-state units will probably emerge as the more compact and economical system.

Suppliers of control components and special control systems for solar heating include long-established firms in the general control business as well as new companies and groups specializing in specific solar control equipment. A representative list of companies offering differential temperature controllers and complete solar control systems is shown in Table 21-2.

Table 21-2
Selected Suppliers of Solar Heating Controls

- Barber Coleman
- Deko Labs
- Heliotrope General
- Honeywell
- Penn Controls
- Rho Sigma
- Robertshaw Controls Company
- Solar Controls (formerly Zia Associates)

HEAT STORAGE

Another important component of the solar heating system is the heat storage unit, but there appears to be no commercial offering of that item. In the liquid system, a conventional tank of some type is purchased. With the air system, a bin is usually constructed on site by the contractor and filled at a suitable time with screened gravel.

COMPLETE SYSTEMS

Several collector manufacturers also provide complete solar heating systems. Their products consist of collectors, accessory hardware for collector support and connection, pumps and/or blowers, preassembled fluid handlers comprising motors, blowers, automatic dampers, filters, water heating coils (for the air system), and motors, pumps, automatic valves (for the liquid system), and controls, including sensors and circuitry for actuating the various motors in the system. Some companies also supply water heating accessories, including heat exchanger and tanks, when that option is involved. The suppliers of complete solar heating systems do not usually furnish a heat storage unit, because its size and local availability usually make its local procurement more practical. Sizing, layout, and detailed design are also offered by some system suppliers. These firms provide the information necessary for installation of their equipment by heating and plumbing contractors having little or no experience in solar equipment installations. Table 21-3 lists a few of the known suppliers of complete solar heating systems.

Table 21-3
Selected Solar Heating System Suppliers

Name of Firm	Type of System
Daystar	Nonfreezing liquid collection and storage
General Electric	Nonfreezing liquid collection and storage
Honeywell	Nonfreezing liquid collection and storage
Piper Hydro	Water collection (nondraining) and storage
Reynolds	Water collection (drainable) and storage
Solaron	Air collection, pebble-bed storage
Solar Utilities Co.	Water collection (nondraining) and storage

EQUIPMENT PERFORMANCE DATA

Most of the suppliers of solar heating system components provide technical data on their performance. Most of the collector data sheets contain information on solar heat collection efficiency at various temperatures and radiation levels. Some include information and instructions for sizing solar heating systems and installation procedures. At least one firm offers an extensive manual covering its products, instructions on their selection and sizing, and their assembly, installation, and servicing.

It should be recognized that some of the manufacturers' literature contains information which has not been verified by impartial analysis, and that the data may not be representative of performance under typical operating conditions. The user is advised to proceed with caution in applying manufacturers' performance figures that have not been independently verified.

Standardized procedures and instrumentation for testing solar equipment have been developed by the National Bureau of Standards (NBS) and are described in two reports:

1. "Method of Testing for Rating Solar Collectors Based on Thermal Performance", NBSIR-74-635. Hill and Kusuda, Center for Building Technology, NBS, December 1974, Interim report prepared for the National Science Foundation.
2. "Method of Testing for Rating Thermal Storage Devices Based on Thermal Performance", N3SIR-74-634. Kelly and Hill, Center for Building Technology, NBS, March 1975, Interim report prepared for the Energy Research and Development Administration.

Although the testing procedures described in these reports are not mandatory for the rating of equipment, they are being accepted by governmental purchasers of solar equipment.

Numerous solar collectors of the liquid heating type have been tested independently by the NASA-Lewis Research Center in Cleveland. Reports of their performance over a range of conditions are available and can be used as a guide to equipment selection. These test results may also be compared with the performance claimed by the manufacturers in their data sheets. Additional testing of liquid heating collectors is also in progress in several independent laboratories.

There have been no independent evaluations and tests of solar air heaters, but facilities are being established at the National Bureau of Standards and at the NASA-Marshall Test Center in Huntsville, Alabama.

Facilities for testing and evaluation of complete solar heating systems are extremely limited. Colorado State University has three identical residential-type buildings in which various systems are being developed and evaluated. This program is producing information which can guide the choice of general system type, and will also yield detailed operating data on specific systems.

SELECTION OF COMPONENTS AND SYSTEMS

Choice of equipment for solar heating involves a knowledge of the characteristics that are significant (and critical) and the advantages and disadvantages of each system type. Besides the information contained in this manual, reference may be made to a helpful government publication, "Buying Solar", published by the Federal Energy Administration, June 1976.

Among the factors most important in equipment choice are the quality of materials and workmanship in the collector, controls, and fluid-handling equipment, the suitability of the materials and equipment to the application (involving such factors as durability, dependability, and safety), heat recovery efficiency over the range of operating conditions encountered, equipment cost, and installation cost.

SELECTION OF SYSTEMS

The system types requiring choice are primarily the flat-plate liquid-heating collector and associated equipment, and the flat-plate air-heating collector with its pebble-bed storage and air handling facility. Another possible choice is a system incorporating an evacuated glass tubular collector in either an air heating or water heating system. So-called passive systems involving collection and storage of heat by materials on or in roofs and walls of buildings rarely are candidates for selection because (a) their practicality has not been proven, (b) there is no manufacturer of such equipment, and (c) if used, these systems are essentially part of the building rather than a heating system. Finally, a system based on use of a focusing collector, although one is commercially available, would seldom be a candidate for residential use because of high cost, tracking requirements, and maintenance demands. Even for commercial buildings, the high cost is a deterrent to general use.

QUALITY OF MATERIALS AND WORKMANSHIP

Durable materials and high-quality workmanship are necessary for efficient, trouble-free operation of solar-heating systems. Visual inspection will often separate the good and poor equipment. Other criteria are records of satisfactory use in previous installations, compliance with minimum property standards, and recommendations from impartial specialists. With liquid systems, the collector, storage unit, heat exchangers, if used, and pumps and piping should be made of materials which are completely compatible with the liquids being used in order that corrosion will not prematurely damage or destroy the system or its components. The collector and other parts of the system must also be able to withstand the maximum and minimum temperatures to which they are exposed. The absorber plate in an efficient collector of the flat-plate type can reach temperatures above 350°F when fluid circulation is interrupted accidentally or purposely, and there should be no material in the collector not capable of withstanding no-flow temperatures for prolonged periods. Wood or other materials which can outgas at these temperatures should never be used in a solar collector. If inspection shows the presence of such materials, the collector is clearly unsuited to normal space heating applications.

SELECTION OF COLLECTOR

The efficiency of the collector in recovering solar energy in a heated fluid is the primary determinant of the size of collector required for supply of a particular fraction of the total heat requirements of a building. And, although this is an important criterion for collection selection, installed cost per unit area is equally significant. Assuming two styles of collectors have equal durability, the one having the greater heat delivery per dollar of first cost is the superior choice, regardless of the efficiency and the cost themselves. In other words, an increase of a few percentage points in efficiency which might be achieved by doubling the cost per square foot is not advantageous. The purchaser should therefore base the choice among various collectors of the general type selected on reliable efficiency measurements, delivered price of the collectors, and the cost of installation determined by the installer's bid or the cost of installing similar systems in other buildings. Unless the solar collection efficiency claimed by the manufacturer has been independently verified or reliably confirmed by theoretical analysis, it should not be accepted without question.

As noted in Module 14, the sizing of a solar collector and associated equipment for carrying a certain fraction of the total heating load cannot be based on some collector efficiency measurement at "ideal" conditions characterized by a full sun nearly perpendicular to the collector and at small to moderate temperature difference between collector fluid and the surrounding atmosphere. Seldom is the collector operating at such favorable conditions in normal use, so average efficiencies are far below such a level. In the selection of solar equipment, however, performance of collectors among a single general type can be compared at the ideal conditions. If collector efficiency is reported over a range of solar intensities and temperature conditions, comparison can be made at poor operating conditions as well as the better ones.

The two items probably most commonly overlooked in the selection of solar collectors and other system components are the durability, or apparent useful life, of the equipment and the cost of its installation in the building. The annual cost of ownership of the equipment is approximately inversely proportional to the useful life. In other words, if a solar collector must be replaced in 15 years, there is no advantage in its purchase at half the price of another collector having a 30-year life. Numerous collectors are on the market today which cannot be expected to operate satisfactorily even for 10 years, so their purchase at prices as low as $5 per square foot appears unwise. A collector which costs $12 to $15 per square foot that can be expected to function satisfactorily over the entire life of the building is a far better investment.

COMPARISON OF SYSTEM TYPES

The two major types of systems now available commercially are those which employ a liquid for transfer of heat from collector to storage and those which utilize air for the same purpose. The so-called passive types, in which collection and storage are combined, are not commercially manufactured because they are so closely associated with the design and construction of the building that they are primarily architectural considerations.

Nearly all of the air and water system types involve collectors employing flat-metal absorber plates overlaid with flat-glass sheets. A modification of this design is applied in the several variations of the evacuated tubular collector for air or water heating. A focusing type of collector employing a transparent plastic Fresnel lens is also receiving specialized experimental use.

ADVANTAGES OF LIQUID SYSTEMS

In comparing air and liquid handling in systems, each has advantages and disadvantages. The primary advantages of the liquid system are due to use of a low-cost fluid with high heat capacity. Relatively small piping for transferring heat from collector to storage and from storage to the heated space in hydronic distribution systems is an economic advantage, particularly in large buildings. The volume of water in which a given quantity of heat can be stored is much less than required of any other material not undergoing a phase change of some type. Heat storage in materials undergoing phase changes is not commercially practical, so water is the most compact heat storage material now available.

Another advantage of the liquid system is its capability for solar air conditioning. Although such systems are not fully developed, they do have practical possibilities, particularly in larger industrial and commercial buildings. An additional advantage in the liquid system is the number of commercial manufacturers of liquid heating solar collectors. Various styles, materials (aluminum, copper, and steel), transparent coverings (glass, plastic films, and heavy plastics), and sizes are available. Finally, a large amount of experience is available with liquid collectors (originally used for hot-water supply), including theory as well as practice.

DISADVANTAGES OF LIQUID SYSTEMS

The disadvantages of liquid systems result primarily from the chemical and physical properties of water. Its freezing point, boiling point, and chemical reactivity with metals require designs and materials which can add substantial cost to a solar heating system. In nearly all parts of the United States, water would occasionally freeze in a solar collector and cause extensive damage. A fail-safe drainage system must, therefore,be provided if water is used in the collector, or a non-freezing liquid must be used, with heat exchange to water storage in a part of the building where freezing cannot occur. A self-draining collector imposes some design restrictions, and the periodic filling of the collector tubes with air imposes limitations on the types of metal which can be used. Nonaqueous heat transfer liquids may be used in the collector loop, but their practical utility has yet to be adequately demonstrated.

The corrosiveness of water in contact with aluminum or steel, in the presence of air, is a factor which must be considered in the design and use of water-heating solar collectors. Galvanic corrosion (in the presence of other metals) of aluminum in water must be avoided by suitable non-conducting connections in the system. Pitting corrosion of aluminum in the presence of slight metallic impurities as well as dissolved oxygen and impurities in the water may result in early failure of the aluminum tubes, particularly if thin-walled. Breakdown of anti-freeze solutions (ethylene glycol, for example) to acidic compounds can accelerate corrosive attack and must be avoided by suitable preventive maintenance.

Steel is less subject to attack than aluminum, but precautions must nevertheless be taken. The probable life of a steel collector is greater than that of an aluminum collector having the same tube thickness. Periodic draining and filling with air must, however, be avoided. Copper, at least for tubes, appears to be the most durable and dependable material. The only disadvantage is its substantially higher cost. A plate-type copper collector requires an outlay roughly three dollars per square foot in excess of that for aluminum. At the retail level, this difference could be as much as five to six dollars in selling price.

With any of the metals used for water-heating collectors, corrosion inhibitors can be added to the solution (whether freeze-protected or not), thereby substantially extending the life of the equipment. The inhibitor itself, however, must be maintained at suitable concentration by periodically checking and adding when necessary.

Another disadvantage of the water system is the boiling which occurs if circulation is lost during sunny weather. The system must be designed with appropriate vents or relief valves to permit discharge of steam when these failures occur. If the condition persists for several hours, there can be so much loss of fluid that recharge is then necessary. For typical residential and commercial installations, a maintenance man would have to be called, and additional antifreeze agent (if used), corrosion inhibitor, and water would have to be added. These requirements impose costs which must be considered in any comparison of systems.

In a well-designed and maintained liquid system, damage to the building and its contents from liquid leakage should not occur. However, poor maintenance or careless operation can contribute to leakage of the collector fluid or of water from the storage system through one of many joints and connections, or through corrosion sites, and can result in expensive damage. Good preventive maintenance is therefore a primary requirement of satisfactory operation of a liquid system.

ADVANTAGES OF AIR SYSTEMS

The advantages and disadvantages of an air system are essentially the reverse of those associated with a liquid system. Advantages are the absence of problems associated with corrosion, freezing, boiling, fluid replacement, monitoring of fluid composition, and potential damage by system leakage.

DISADVANTAGES OF AIR SYSTEMS

A disadvantage of the air system is the larger volume required for heat storage - approximately three times that for the equivalent heat storage capacity in water. This requirement imposes a need for floor space having a linear dimension approximately 60 percent greater than for a cylindrical storage tank. Equal heat storage can be provided, for example, in an eight-foot cube of pebbles and in a tank of water five feet in diameter and eight feet high. Another air system disadvantage is the size of ductwork between collector and storage. About four square feet needs to be available for two ducts between collector and storage in a typical residential installation. A third disadvantage is the current lack of air conditioning equipment operable with a solar-heated air supply. This situation is not yet a deterrent to air system use, however, because no solar air conditioning system is yet commercial.

Comparison of the advantages and disadvantages of solar heating system types outlined above leads to the conclusion that the air system is superior insofar as durability and freedom from maintenance are concerned. Experience with a limited number of systems bears out this generalization. As to compactness and wide availability of hardware, the liquid system appears to be the better choice. These relative advantages suggest that air systems may predominate in residential installations where maintenance is notoriously neglected, where compactness is often not considered essential, and where durability is important. Liquid systems, on the other hand, may predominate in commercial and industrial installations where maintenance is routinely practiced, where space is frequently at a premium, and where occasional equipment replacement is acceptable if economically desirable.

SYSTEM PERFORMANCE

In terms of system efficiency, or annual heat delivered per unit collector area, the two systems have comparable performance. Several studies have shown that the difference in heat output is small, and that one system may be slightly better under some conditions and the other superior in other situations. The most recent information on two identical adjacent houses shows nearly one-third more heat was supplied by the air system from equal collector areas. But a conservative appraisal is that the two systems have approximately equal heat delivery capability per square foot of collector area. More data are needed before more definitive statements can be made.

COST OF HEAT DELIVERED

The final and conclusive basis for comparison is cost per unit heat delivered. If efficiency, useful life, and maintenance costs are equal, the system requiring the least maintenance per square foot of collector is the best choice. System costs are not yet sufficiently established for positive selection on this basis. However, examination of published prices of solar collectors and consideration of the costs of other components in the system suggest that the total installed cost of the air system is lower than that of the liquid system, for equal heat output. Evidence in support of this indication is not conclusive, however, so unless actual quotations can be compared, it should be assumed that the cost difference is not large, possibly not over 10 percent of the total investment, and that any difference is probably in favor of the air system.

Another important factor bearing on solar heat cost is the useful life of the system and the costs of maintenance and repairs. On these points there is little doubt that the air system involves lower annual expense. The absence of corrosion, the use of moderate-priced metal (mild steel), and the absence of servicing requirements indicate that the air system will have a longer life and lower maintenance cost than the liquid system.

With respect to evacuated tubular collectors, their high efficiency is a great advantage. These units are not yet being made for general sale, so it is difficult to make comparisons with flat-plate systems. Manufacturing costs are much higher, and current prices may not reflect true costs. But if these units can be produced in large volume (e.g., a thousand tons of glass per month), costs might reach a competitive level. Selection of evacuated tubular systems today would have to be based on criteria other than cost, such as high temperature delivery of collector fluid at reasonable efficiencies. But when demand reaches the level justifying automated tubular collector production with a furnace used exclusively for this product, costs may become very attractive.

There is also a focusing collector (Fresnel lens) which has received some experimental use. It requires a tracking mechanism and the cost is substantially higher than the other systems. Unless high temperatures, well above 200°F, were a specific requirement as, for example, for absorption air conditioning, there appears to be no advantage in the use of this low-concentration focusing system. The considerably higher cost, inability to focus diffuse radiation, and the need for moving hardware, plus maintenance, appear to preclude its practical use for space heating.

In the final choice of a solar heating system, consideration must be given to the type of use which the system is to meet. As previously indicated, liquid systems appear to have some advantages over air systems in large installations where maintenance is customary and where cooling may now or later be provided by solar energy. Other circumstances might also provide incentives for liquid system use. It is evident that both systems have potential for widespread application.

CRITERIA AND STANDARDS

Although no performance criteria or standards for solar heating equipment have been established, several such efforts are being made. Among the active organizations are the American Society for Testing and Materials (ASTM), the American National Standards Institute (ANSI), the American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. (ASHRAE), the Sheet Metal and Air Conditioning Contractors' National Association (SMACNA), and various government bureaus, including the National Bureau of Standards (NBS), the Department of Housing and Urban Development (HUD), and the Energy Research and Development Administration (ERDA).

A committee of the ASTM and ANSI organizations is actively engaged in formulating standards for solar heating equipment. No results have been publicly released, but criteria or guidelines may be expected.

ASHRAE, through its series of manuals on heating and air conditioning, continues to expand its section on solar heating and cooling. The 1974 edition of "Applications" contains solar heating information and guidelines in Chapter 59. This material is in the form of a reference handbook for designers and installers of solar heating equipment, but it is comparatively general in its content.

An important project of the National Bureau of Standards is the formulation of performance criteria which solar heating and cooling equipment should be expected to meet. Two of the results of this project are the reports, "Interim Performance Criteria of Commercial and Solar Heating and Combined Heating/Cooling Systems and Facilities", NASA 98M-10001, 28 February 1975 (prepared by NBS) and "Interim Performance Criteria for Solar Heating and Combined Heating/Cooling Systems and Dwellings", HUD, 1 January 1975 (prepared by NBS for HUD). These publications contain information on the characteristics of solar systems and components which are important in the selection of equipment. No requirements are outlined, in terms of quantitative performance, but the equipment is expected to perform at the level which the manufacturer or supplier specifies. In addition to the criteria themselves, the reports describe methods for measuring the performance of collectors and heat storage units.

The next government effort along these lines has resulted in the release of "Intermediate Minimum Property Standards Supplement for Solar Heating and Domestic Hot Water Systems," prepared by the National Bureau of Standards for the Department of Housing and Urban Development (HUD). In conformance with other HUD documents of this type, the specifications outlined are those which solar heating equipment will have to meet if federal funds, such as FHA home loans, are used in financing the structure or its components. As with the "interim performance standards" developed by NBS, the solar heating and cooling standards in the HUD document are directed mainly to safety, durability, reliability, and such factors rather than to the specific efficiency of heat supply or other quantitative criteria. The equipment is required to perform according to the manufacturer's claims.

The work being undertaken by SMACNA is directed toward standards for installation workmanship in solar heating systems. Such factors as the quality of the plumbing, sheetmetal work, and electrical work will be considered.

Standards for testing solar equipment have been the subject of work at the National Bureau of Standards for over two years. A useful report of part of this investigation is "Development of Proposed Standards for Testing Solar Collectors and Thermal Storage Devices", NBS Technical Note 899, issued February 1976.

Another document related to standards and criteria, prepared at the Center for Building Technology of the National Bureau of Standards for the Energy Research and Development Administration, Division of Solar Energy, is "Thermal Data Requirements and Performance Evaluation Procedures for the National Solar Heating and Cooling Demonstration Program." This manual provides detailed information and directions for measuring and evaluating the performance of solar heating and cooling systems.

WARRANTIES

The types of warranties offered by manufacturers of solar heating equipment vary considerably. At the present time, if a supplier provides any warranty, it is of the "limited" type. Under its terms, the equipment is warranted to be free of defects in materials and workmanship, and that if such defects are found within a certain period of time after initial use, correction or replacement will be made without cost to the user. Most of the suppliers of solar equipment do not currently offer any type of warranty. A few, larger companies involved in solar equipment manufacture are offering one-year limited warranties. One company marketing an air system offers a 10-year limited warranty.

There appear to be no manufacturer's guarantees as to thermal efficiency or heat delivery capability of solar equipment. Although manufacturers are providing that type of information in their sales literature, they are not guaranteeing the performance in the field. To a certain degree, this omission is due to the inability of the manufacturer to control the quality of the installation. In addition, manufacturers supplying only certain components of a system, such as the collector, cannot be assured that the other components in the system are correctly selected or integrated with their own product. Thus, inferior performance might well be due to factors other than those controlled by the collector manufacturer. A performance warranty would thus be difficult to establish and maintain.

Still another problem in providing a meaningful performance warranty is the great variation in climate encountered and the practical difficulty in accurately measuring the output of the installed equipment. Instrumentation is usually not provided, so measurement of performance is likely to be an expensive investigation by an experienced engineer. Disputes, litigation, and other problems would be inevitable.

Practical performance warranties should become available for complete solar heating systems provided by a single manufacturer, assembled and installed by a single responsible individual or firm. The manufacturer could then guarantee the system to the installing firm which, in turn, would guarantee it to the purchaser. In case of dispute, the installer could measure system performance in the presence of the owner and a third party, if demanded, for determination of conformance. If inadequate, corrections would be made in compliance with the warranty, and the installer and manufacturer would establish responsibility for the departure from specifications.

Such developments as the Home Owners Warranty (HOW) program, sponsored by the National Association of Home Builders, can be expected to have an influence on solar heating equipment guarantees. Under the HOW program, all defects in a residential structure will be corrected at no cost to the owner during the first three years of use. It may be expected that solar heating equipment will have warranties conforming with such a program. Manufacturers will then be required to guarantee to the dealer and installer the necessary support for compliance with this program.

The solar equipment manufacturing industry unfortunately includes several small suppliers having practically no experience with solar equipment and offering no warranties of any kind. Purchasers of such equipment have very little chance of reimbursement for costly failures. Even if a small, marginal manufacturer offers some sort of warranty, a purchaser does not have much assurance that the manufacturer will remain in business long enough to make good on its guarantee. In the event of equipment defect or failure, the owner (or installer,if guaranteed by him), would suffer the loss. These and other topics are discussed in the previously mentioned government report, "Buying Solar", published in June 1976 by the Federal Energy Administration and HUD.

TRAINING COURSE IN

THE PRACTICAL ASPECTS OF

SIZING, INSTALLATION, AND OPERATION OF SOLAR HEATING AND COOLING SYSTEMS

FOR

RESIDENTIAL BUILDINGS

MODULE 22

FUTURE PROSPECTS FOR SOLAR HEATING AND COOLING SYSTEMS

SOLAR ENERGY APPLICATIONS LABORATORY

COLORADO STATE UNIVERSITY

FORT COLLINS, COLORADO

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INTRODUCTION

The solar systems that are described in other modules of this manual are cost-effective systems that have been installed and operated. Data obtained from experimental systems indicate that they function satisfactorily in residential buildings. Fluids that are heated by solar energy in flat-plate collectors are sufficiently high in temperature to heat space and hot water and to provide the hot water to drive an absorption cooling machine. Although efficiencies of the systems vary, they are generally about 30 percent and, while such an efficiency is satisfactory, if it can be improved by better components at lower energy cost, the improvements are worthwhile. A number of new features and components of systems are being researched and many could improve system performance significantly. Flat-plate collectors can be improved with selective coatings or redesigned to provide greater efficiencies in heat collection. Storage with latent heat materials could provide greater heat capacity in more compact space, and storage for liquid systems with direct contact heat exchanger to eliminate some hardware would improve system performance. If air conditioning equipment using solar-heated air could be developed, the air-heating solar systems could be used throughout the year for heating and cooling. These and many other future prospects are in store for solar heating and cooling systems.

OBJECTIVE

This module describes some prospective features and components in solar heating and cooling systems that could improve overall system performance. The objective of the trainee is to know some of the new features that could become economical to add to the systems described in this course and to recognize that considerable research and development effort is being devoted to component hardware in solar heating and cooling systems.

SOLAR COLLECTORS

The most important component in a solar system which could improve performance is the solar collector. Improvements which will increase efficiency of energy collection and reduce the delivered costs are particularly worthwhile. Among many interesting possibilities are the addition of selective surfaces to absorbers, and collectors with the air evacuated from around the absorber plates to reduce heat losses and improve collector efficiency.

SELECTIVE SURFACES

Selective surfaces have high absorptance of solar radiation and low emittance of long-wave radiation. There are a variety of selective surfaces that could be used in flat-plate collectors, and some are being tested on experimental units. Several coatings such as copper oxide and black nickel have been available for a long time, but technical problems and cost have limited their use. Black chrome appears to hold some promise and some flat-plate collectors are presently available with such absorber coatings. Characteristics of some selective surfaces are listed in Table 22-1.

Table 22-1
Selective Surfaces Characteristics

Coating	Absorptance	Emittance
Converted Zinc	0.90	0.071
Black Nickel	0.88	0.066
Black Chrome	0.92	0.085

EVACUATED TUBE COLLECTORS

Evacuation of the air around the absorber plate is potentially a significant improvement in solar collectors. There are a number of different designs that are being assembled and tested, and at least one manufacturer makes them in moderate quantities. Evacuated collectors will produce more useful heat than standard flat-plate collectors under the same sun and weather conditions because the losses from the absorber are greatly reduced. With a vacuum surrounding the absorber, conduction and convection losses are effectively negligible and, if the absorber coating is a selective surface, the radiation loss is small.

One design, by Corning Glass Works, is shown in Figure 22-1. Inside an evacuated glass tube which is four inches in diameter is a copper absorber plate with a selective surface. Bonded to the plate is a copper U-tube which carries the heat transfer fluid. The ends of the tube protrude through one end of the glass tube,and the absorber plate is free to expand toward the other end. The efficiency range of the collector varies from about 75 percent when the inlet fluid temperature is low to about 60 percent when the fluid is near the boiling temperature of water. Most flat-plate collectors have high efficiency with low inlet fluid temperatures, but have low efficiencies when the fluid temperature is near 200°F. The evacuated tube collector has a

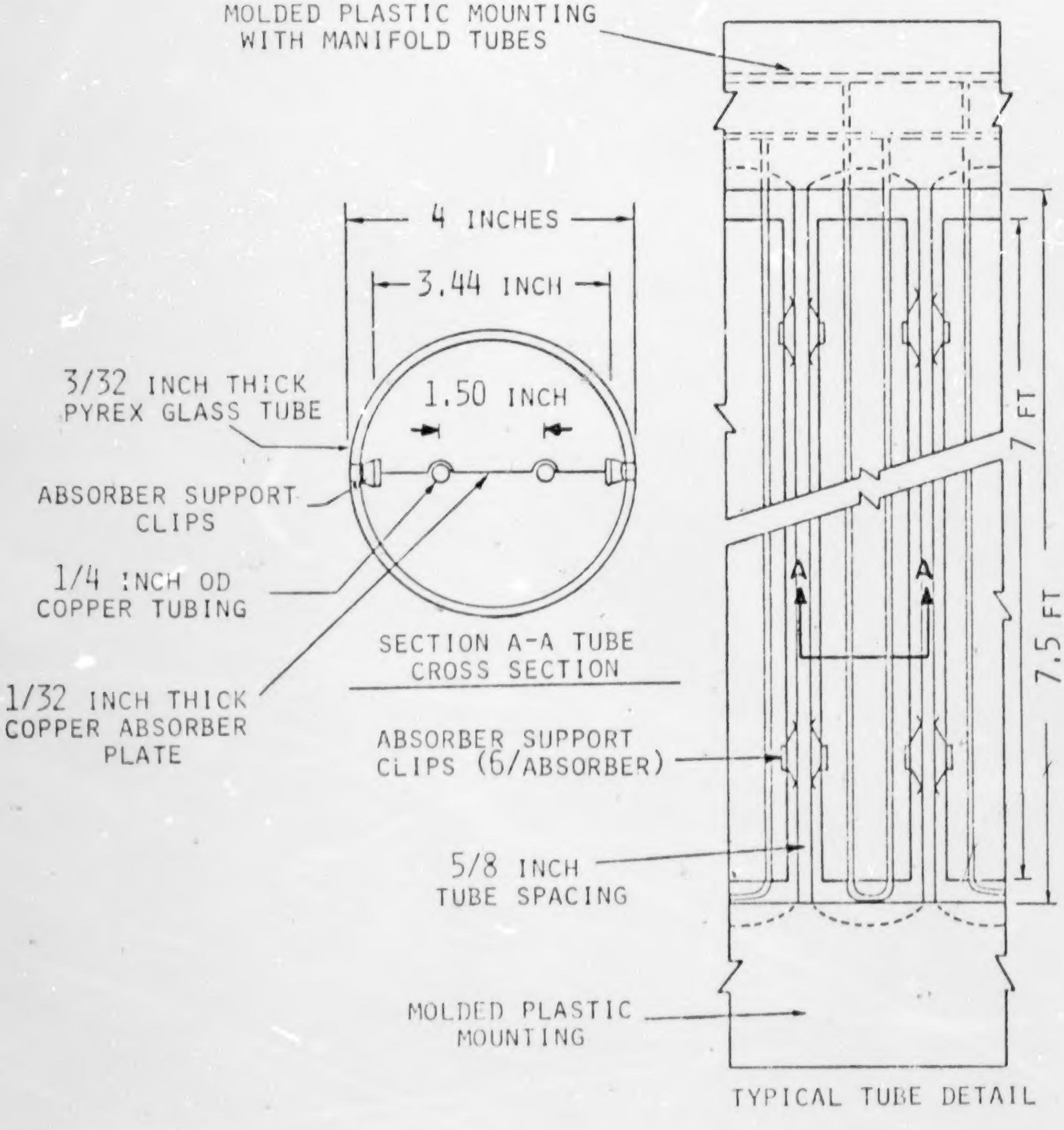
MOLDED PLASTIC MOUNTING WITH MANIFOLD TUBES
4 INCHES
3.44 INCH
3/32 INCH THICK PYREX GLASS TUBE
1.50 INCH
ABSORBER SUPPORT CLIPS
1/4 INCH OD COPPER TUBING
1/32 INCH THICK COPPER ABSORBER PLATE
SECTION A-A TUBE CROSS SECTION
A
A
7 FT
7.5 FT
ABSORBER SUPPORT CLIPS (6/ABSORBER)
5/8 INCH TUBE SPACING
MOLDED PLASTIC MOUNTING
TYPICAL TUBE DETAIL

Figure 22-1. Schematic of the Corning Glass Works Evacuated Tube Solar Collector

significant advantage when producing high temperature heat to the system and can be used effectively with solar cooling units where high temperature fluid is needed.

An evacuated tube collector design by the Owens-Illinois Glass Company is shown in Figure 22-2. There are three concentric glass tubes with the intermediate one coated with a black selective surface. The vacuum is between the outer and intermediate tubes. Fluid is transported through the inner tube and, as it passes through the annulus in contact with the absorber tube, heat is transferred from the glass to the fluid.

Two other evacuated tube collectors are being experimentally tested, one by the General Electric Company for use in air-heating systems and another is by the Philips Company in West Germany for liquid systems. Many variations in design of evacuated tube collectors are possible, and different designs will gradually advance to the practical stage.

CONCENTRATING COLLECTORS

Concentrating collectors are used when very high temperature fluid is needed to drive heat engines or to be used in industrial processes. If concentrating collectors can be designed to be more efficient than flat-plate collectors, operate reliably, and with little maintenance so that the cost of delivering energy is low, then such collectors can have potential uses in residential solar systems. Experience thus far has indicated otherwise, but there is considerable research underway and new designs for concentrating collectors are being developed.

One type of low concentration collector is being developed by the Northrup Company and is being tested on a number of solar systems for large buildings. A linear focusing collector with a Fresnel lens is the type being developed and is shown in Figure 22-3. The collector is

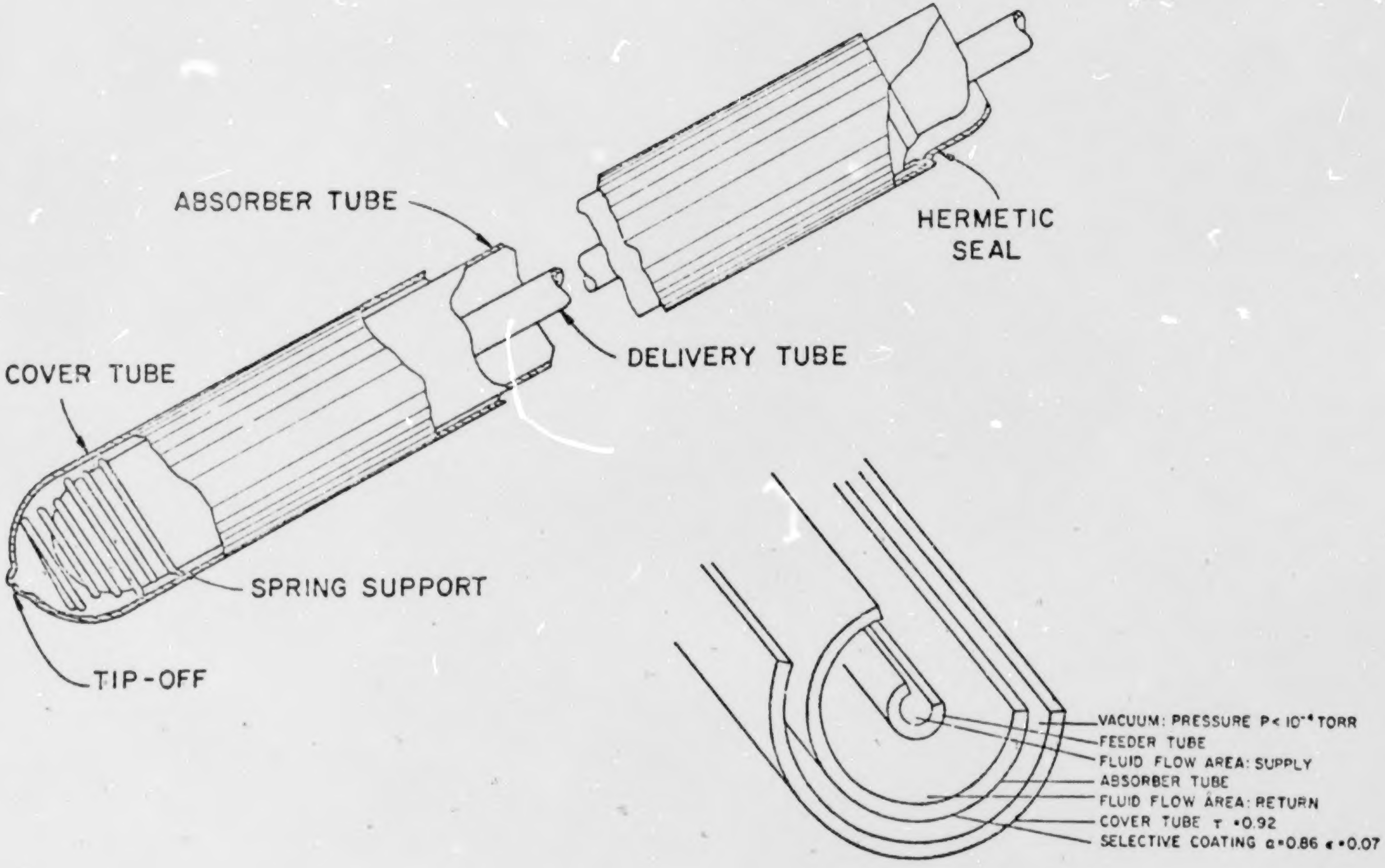
ABSORBER TUBE
HERMETIC SEAL
DELIVERY TUBE
COVER TUBE
SPRING SUPPORT
TIP-OFF
VACUUM: PRESSURE P< 10⁻⁴ TORR
FEEDER TUBE
FLUID FLOW AREA: SUPPLY
ABSORBER TUBE
FLUID FLOW AREA: RETURN
COVER TUBE τ = 0.92
SELECTIVE COATING α = 0.86 ε = 0.07

Figure 22-2. Schematic of the Owens-Illinois Evacuated Tube Solar Collector

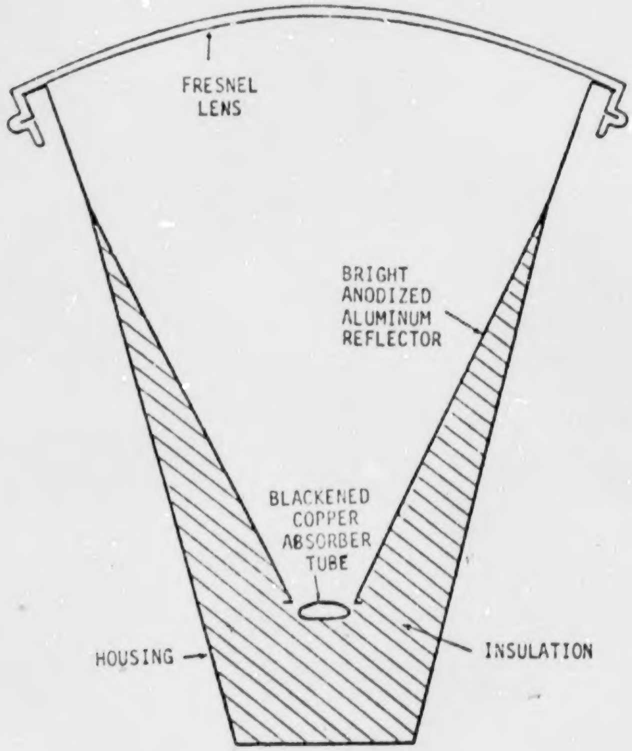
FRESNEL LENS
BRIGHT ANODIZED ALUMINUM REFLECTOR
BLACKENED COPPER ABSORBER TUBE
HOUSING
INSULATION

Figure 22-3. Fresnel Lens Strip Solar Collector

mounted with the axis in the north-south direction and tilted at an angle with respect to the horizontal plane. The collector rotates from east to west during the day so that the direct rays from the sun are focused into the absorber tube. A distinct disadvantage of concentrating collectors is that only the direct rays from the sun are used, as the diffuse radiation cannot be focused.

THERMAL STORAGE

Considerable research is being devoted toward the utilization of salt hydrates and other phase-change materials for storage of latent heat. The principal difficulties are packaging the storage material and stratification or separation of the material after a few hundred cycles of phase changes. One advantage in the use of phase change materials is supposedly the smaller storage volume required, as compared to water or rocks. However, a solar heating and cooling system requires a water volume of only two gallons of water or one-half cubic foot of rocks per square foot of solar collector area and, in a typical system with 500 square feet of collectors, the water volume needed is about 1000 gallons or about 350 cubic feet of rocks. When packaged phase-change material is arranged in a container with adequate surface contact with the heat transfer fluid from the collectors, it is difficult to achieve a significantly smaller volume of storage.

With proper materials there is, however, an advantage in being able to obtain a sustained constant temperature of the heat delivered from storage. This property of latent heat storage materials can be used to advantage in solar cooling systems, both in the hot storage and cold storage tanks.

Another future prospect for storage of thermal energy is in chemical methods. Chemical storage offers technical possibilities that sensible and latent heat storage do not. These possibilities include: (1) long-term storage without need for insulation and without thermal loss, (2) storage at high energy density, and (3) recovery of stored thermal energy at temperatures above or below the original temperature. Although no thermo-chemical system appears imminent, in concept at least, this method of storage can have important applications in terms of supply and demand and improving thermal efficiency.

HEAT EXCHANGER

The disadvantage of a heat exchanger in present liquid-heating solar systems is the temperature difference needed to transfer the heat at the heat exchanger. A temperature difference of 10 to 20°F has a significant influence on the amount of useful heat delivered by the system. The temperature in storage is low and the collector efficiency is less.

A heat exchanger-storage combination unit is under investigation where heat is transferred from liquid droplets that transport heat from the collector to water in the storage tank. A liquid that is immiscible in water is pumped through the solar collector and through the storage tank as droplets. If the density of the liquid is substantially different from that of water, the liquid droplets will either rise or descend through the water in the storage tank. A schematic of a heat exchanger-storage unit is shown in Figure 22-4. For the illustration shown, the

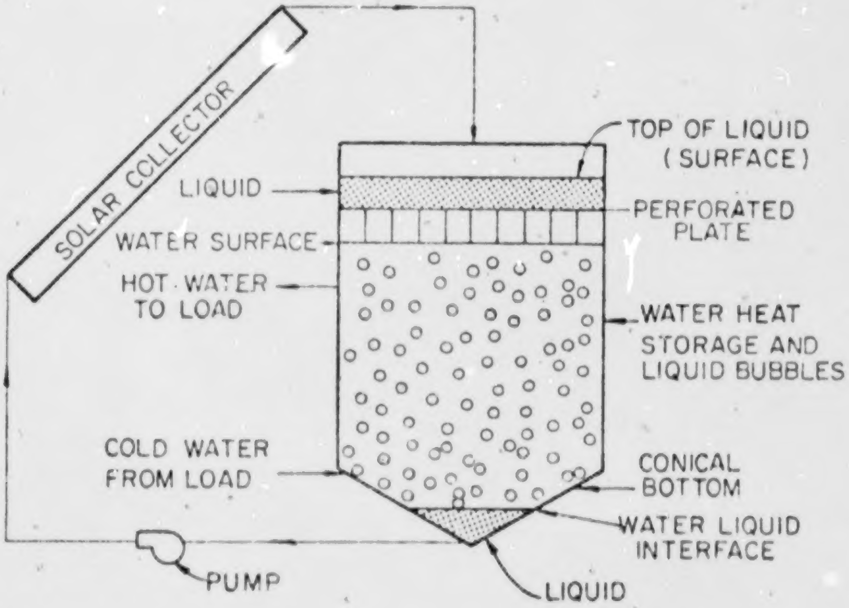
SOLAR COLLECTOR
TOP OF LIQUID (SURFACE)
LIQUID
PERFORATED PLATE
WATER SURFACE
HOT WATER TO LOAD
WATER HEAT STORAGE AND LIQUID BUBBLES
COLD WATER FROM LOAD
CONICAL BOTTOM
WATER LIQUID INTERFACE
PUMP
LIQUID

Figure 22-4. Direct Contact Liquid-Liquid Heat Exchanger

liquid is heavier than water. The liquid is delivered to the top of the tank, is broken up into droplets at the perforated plate, and collects in the bottom cone. The temperature difference between the droplets and the storage water is only about 1°F or less, with substantial heat transfer occurring across the large collective area of the droplets. There are several possible liquids that can be used and, although not named, their properties and approximate costs are listed in Table 22-2.

Table 22-2
Properties of Possible Collector Fluids

Fluid	Freezing Point (°F)	Boiling Point (°F)	Specific Gravity	Cost ($/gal)
1	-31	698	1.116	2.98
2	-36	734	1.208	6.91
3	-31	644	1.048	3.32
4	-41	568	1.120	3.46
5	-27	415	1.043	10.45
6	-13	770	1.162	8.63
7	-76	782	0.927	3.79
8	-67	478	0.913	9.80

SYSTEMS

At present the only commercially available cooling unit in small size that is operable with solar energy is a lithium-bromide absorption cooling unit. As mentioned elsewhere in this manual, there are a number of different experimental cooling units that are being developed, such as the heat engine-driven refrigeration machine and ammonia-water continuous cycle unit.

There is also significant effort being made in the development of so-called total energy systems, where high temperature heat from solar energy is used to generate electricity and the low temperature "waste" heat is used to heat and cool a cluster of buildings. Such systems are likely destined for specialized use in grouped facilities such as military bases but, with some variation, may serve a number of homes or apartment complexes.

In the long term, development of photovoltaic systems for residential buildings is a possibility. Electricity that is generated could operate the heating and cooling system in the house. Whether photovoltaic systems will ever be low enough in cost to be competitive with electricity generated from fossil or nuclear fuels is an open question, but a considerable amount of effort is being devoted to improve efficiency and reduce the costs.

Other improvements in systems which utilize solar energy are hybrid systems consisting of passive as well as active components. There has not been much effort toward development of passive systems except by architectural treatment of windows. While this effort has been significant, more direct heating of residential space with passive systems may minimize the size of the active components and thereby reduce overall costs.

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